DOCUMENT RESUME

ED 303 373 SE 050 364

TITLE	Educational Technology Center Fifth Year Report.
INSTITUTION	Educational Technology Center, Cambridge, MA.
SPONS AGENCY	Office of Educational Research and Improvement (ED), Washington, DC.
REPORT NO	ETC-TR-88-30
PUB DATE	Nov 88
CONTRACT	OERI-400-83-0041
NOTE	134p.; Figures and graphs may not reproduce well.
PUB TYPE	Reports - Descriptive (141)
EDRS PRICE	MF01/PC06 Plus Postage.
DESCRIPTORS	Cognitive Processes; Computer Assisted Instruction; Computer Simulation; *Computer Uses in Education; Elementary School Science; Elementary Secondary Education; *Learning Strategies; Networks; *Research and Development Centers; *Research Projects; Science Instruction; *Scientific Concepts; Secondary School Mathematics; *Secondary School Science; Teacher Effectiveness; Technology
IDENTIFIERS	*Educational Technology Center MA

ABSTRACT

The Educational Technology Center (ETC) has devoted the last five years to studying ways of using the computer and other information technologies to teach understanding in science, mathematics, and computing in the nation's elementary and secondary schools. The Center's research has focused on targets of difficulty, topics and concepts that are both central to their disciplines and recognized by teachers and students as difficult to teach and learn. By seeking to apply new technological capabilities at these particular points in the curriculum, they have attempted to make a real difference in the ability of schools to educate students. From the beginning it was realized that making a difference in schools would require a different sort of research and development approach than had previously been tried in science and mathematics education. A framework and five-point focus has become the hallmark of the Center's work: (1) subject matter; (2) student's ideas about subject matter; (3) teaching for understanding; (4) technology; and (5) implementation. This document presents summaries of the work of individual research projects. Work is summarized for the first four years of research and the fifth year is presented and discussed with implications for practice and future research. (MVL)

EDUCATIONAL TECHNOLOGY CENTER

FIFTH YEAR REPORT

NOVEMBER 1988

Preparation of this report was supported in part by the Office of Educational Research and Improvement (Contract # OERI 400-83-0041). Opinions expressed herein are not necessarily shared by OERI and do not represent Office policy.

Table of Contents

INTRODUCTION

The Educational Technology Center has devoted the last five years to studying ways of using the computer and other information technologies to teach for understanding in science, mathematics, and computing in the nation's elementary and secondary schools. The Center's research has focused on targets of difficulty, topics and concepts that are both central to their disciplines and recognized by teachers and students as difficult to teach and learn. By seeking to apply new technological capabilities at these particular points in the curriculum, we have attempted to make a real difference in the ability of schools to educate students.

From the beginning, however, we realized that making a difference in schools would require a different sort of research and development approach than had previously been tried in mathematics and science education. Determined to avoid the implementation problems that plagued reform efforts of the 1960s and 1970s, ETC adopted a collaborative mode of operation that called upon the diverse talents and viewpoints of practicing teachers, subject matter specialists, technology experts, educational researchers, and curriculum and software developers. These groups evolved a framework and five-point focus that has become the hallmark of the Center's work:

- **Subject Matter:** Identification of the key concepts within a discipline and analysis of the subject matter to determine when and why these concepts cause trouble for students and teachers. Also, identification of the important modes of representing knowledge, conducting inquiry, and evaluating evidence within a discipline.

- **Students' Ideas about Subject Matter:** Study of the ideas about scientific and mathematical phenomena that students bring to the classroom. Examination of the ways these ideas differ from accepted scientific theories and thus of the kind of reconceptualization students must undergo.

- **Teaching for Understanding:** Creation of teaching approaches that present new subject matter in a way that takes account of students' ideas and promotes conceptual change. Integration of directed instruction with opportunities for students' inquiry and attention to how knowledge is created within a discipline. Revision and refinement of materials and strategies based on clinical interviews and classroom experiments.

- **Technology:** Use of technology where it can make a unique contribution to teaching and learning, for example, by enabling multiple representations of mathematical concepts, presenting conceptual models of scientific phenomena, and extending the range of manipulable objects. Integration of technology-enhanced teaching with traditional methods and materials.

- **Implementation:** Consideration at all stages of research and development of the difficulties and opportunities of introducing innovative approaches into regular classrooms. Investigation of the supports and resources needed for ETC approaches to work effectively in schools.

During Years One through Four of ETC's life — and in the annual reports on those years' work — we divided our efforts among the five tasks outlined in the original Request for Proposals that gave rise to the Center: (1) Agenda Building; (2) Research on Science, Mathematics, and Computing; (3) Research on New Technologies; (4) Training; and (5) Dissemination. In this fifth and final year of our funding from the U.S. Office of Educational Research and Improvement (OERI), the Center's work has emphasized the synthesis of results from our research and the dissemination of our findings to appropriate audiences. Thus, in this report we have omitted separate sections on agenda building and training, activities that have been subsumed and integrated into our synthesis and dissemination efforts.

The heart of this document, as usual, is the summaries of the work of individual research projects. Each discusses its target of difficulty and how that target has evolved over the life of the project; explains how it has incorporated technology into its pedagogical approaches and solutions to teaching and learning problems; summarizes its work over the first four years of research; describes its activities in Year Five; and discusses its overall conclusions with implications for practice and for future research. These sections tell the full rich story behind research activities and findings such as these:

• *Development and study of the effects of computer simulations that visually represent normally unobservable aspects of scientific phenomena.* The Center's research has explored how such models can help students to change their deeply rooted everyday ideas -- sometimes referred to as alternative frameworks — and to more readily grasp important accepted scientific theories and concepts. Through clinical interviews, researchers probed students' ideas about weight and density and heat and temperature, both to find out what young people already know and believe about these phenomena and to see how their ideas differ from the textbook theories they are expected to learn in science class. Research groups then developed interactive computer-based conceptual models that explicate and represent these scientific concepts within an environment in which students can make and test hypotheses. For example, although density is unobservable in the real world — students must infer it from their knowledge of weight and size — the ETC Prototype Weight/Density software represents density in a visually quantifiable way.

Classroom studies suggest that the weight/density simulations help students to move through five predictable levels of understanding the distinction between these two concepts. Initially attending only to weight and making no distinction between weight and density, most youngsters gradually learned the differentiation, and many were able to apply it under all conditions, including thermal expansion.

In classroom studies of the effectiveness of Prototype Heat/Temperature Software, students who used the computer models displayed a better grasp than control students of the differences between heat and temperature, especially the extensivity of heat and the intensivity of temperature. They correctly used the concept of amount of heat, their knowledge was better integrated, and they made better predictions about novel situations.

• *Study of students' alternative frameworks about the construction of scientific knowledge and creation of teaching materials to enhance their understanding.* For example, researchers found that most junior high school students think the purpose of science is to discover new inventions and cures. Most have no notion of science as the intellectual construction of theories, no sense of experiments as tests of ideas, and no differentiation of hypotheses, experiments, and results. Researchers designed a curricular unit not only to teach students how to carry out controlled laboratory experiments but also to address metaconceptual points about the nature and purpose of scientific inquiry. Students who have used this curriculum learn as much as those taught by traditional means about the scientific method, and they learn more about the nature and purpose of science.

• *Use of the computer's power as a representational medium to enable the creation of a "concrete-to-abstract software ramp."* This makes possible a longitudinally coherent approach to teaching students the web of mathematical ideas connecting the topics of rate, ratio, proportion, and intensive quantity. The software series created at ETC starts at the level of concrete icon-based calculation, then links this iconic representation of quantities with other more abstract and mathematically powerful representations such as tables of data, coordinate graphs, and algebraic equations. Originally envisioned as an environment for solving word problems, the software series now in prototype form spans several grade levels, taking students from the rudiments of multiplication, division, and ratio reasoning through pre-algebra. Results so far suggest that the external visual representations presented by the software help students to construct more sophisticated mental representations of the target mathematical ideas.

• *Study of the use of software that permits students to build, manipulate, and learn from educationally powerful objects that are otherwise impossible or impractical in the classroom.* For example, the Center has demonstrated the potential of software entitled the *Geometric Supposer* (developed at Education Development Center and available from Sunburst Communications, Inc.) to reintroduce an empirical component into the teaching and learning of geometry. This software eliminates the tedium of compass and straightedge, enabling students to make quick, accurate geometric constructions and measurements. Because they can quickly generate large amounts of geometric data, students are able to make and test their own conjectures about geometric relationships, rather than simply memorizing theorems and proofs in their textbooks. Studies have shown that on tests of ability to provide arguments and formulate hypotheses, students who used the *Supposer* within an inquiry-based approach to learning geometry were far more likely than their counterparts in traditional classes to make conjectures about large sets of cases and to provide formal proofs.

• *Examination of students' misinterpretations of graphical representations of algebraic functions,* which sometimes lead to incorrect inferences about the relationship between graphs and functions. Using software (under development at Education Development Center) that links symbolic mathematical expressions with their graphic representations, researchers have found that issues of scale often confuse students and are now developing teaching approaches to help students overcome this confusion.

• *Identification of the principle problems of beginning programming students and development of teaching materials to ameliorate these problems.* First, beginning students have difficulty reading programs and predicting how the computer will carry them out.

This weakness creates problems at all stages of the programming process, including the writing, checking, debugging, and repairing of programs. Second, students have trouble "filing" information about the programming language in a way they can use later — that is, they have trouble putting what they have learned into practice. Having identified these difficulties, ETC researchers developed a metacourse to address them. This metacourse — a series of lessons to be interspersed throughout the regular curriculum for a semester-long beginning course in BASIC — stresses key concepts and mental models that teachers and students can apply to any programming task they encounter. Students who have used scripted Metacourse lessons have outperformed control students on end-of-semester tests of BASIC.

• *Connecting educational research to the improvement of practice through collaborative research and through continuing attention to implementation issues.* Involving experienced teachers as partners in collaborative research requires time and explicit efforts to link the work of schools with the work of universities. ETC established laboratory sites in several schools to learn what implementation of the Center's innovations entails. This research revealed that incorporating technology-enhanced guided inquiry approaches into regular classrooms requires changes not only in technology, but also in curriculum and in teaching approaches. Implementation assistance must therefore include not only logistical help with issues such as schedules, equipment, and curriculum materials. It may also need to support a process of teacher education through which teachers collaboratively rethink educational goals, strategies, and roles and invent ways to connect their own wisdom with the products of educational research.

• *Exploration of the potential of microcomputer-based conferencing to alleviate the isolation of secondary school teachers,* both from one another and from new developments in their fields. Observations of two networks and reports on others indicate different avenues to collegial exchange which require different network management strategies. Among unacquainted teachers who shared no common network tasks, specific information interests predominated, suggesting need for a large membership, guest experts, or access to supplementary information resources. Two other routes to collegial exchange are collaboration on structured tasks or interest in social contact among previously acquainted teachers.

Beyond Year 5

Improving mathematics and science instruction in the nation's schools is more than a five-year undertaking for any organization. Thus, although ETC's five year contract with OERI is ending, the work begun with that funding is far from over. Several projects have already launched the next phase of their work, and others are poised to continue as soon as alternative funding is arranged. The same fundamental assumptions and goals will guide the next five years: attention to subject matter; attention to students' ideas about subject matter; selective use of technology to solve problems of teaching and learning; creation of teaching approaches that promote student inquiry and problem solving; and attention to implementation issues. As in the past, these lines of inquiry will be pursued collaboratively by school-based and university-based participants.

RESEARCH IN SCIENCE, MATHEMATICS, AND COMPUTING EDUCATION

RESEARCH IN SCIENCE EDUCATION

OVERVIEW

ETC's three science projects work closely together to explore a cluster of related areas of conceptual and metaconceptual learning in science. Two projects — Weight/Density and Heat/Temperature — seek to help students learn difficult but important conceptual distinctions that pave the way toward more sophisticated understanding of the physical world and toward higher learning in the physical and biological sciences. The third project focuses on students' understanding of the nature of scientific inquiry and of the thought processes and laboratory skills associated with the construction of scientific knowledge.

All three projects began their work with careful study of students' everyday ideas about their target concepts. Previous research has shown that these ideas — referred to as prior theories or alternative frameworks — frequently remain unchanged despite traditional classroom instruction that presents scientific facts and definitions. This research suggests the need for instructional approaches that take students' theories into account and present new material in ways that promote conceptual reorganization, not simply lay a veneer of new vocabulary over old ideas.

Although the computer can support traditional teaching effectively in many ways — it can simulate laboratory experiments, collect and display data, and tutor students in new vocabulary — ETC research groups have looked beyond these uses to explore ways that technology can help to meet the difficult goal of promoting conceptual change. Two projects — Weight/Density and Heat/Temperature — have devised interactive computer-based models that not only extend students' ability to observe and manipulate the phenomena under investigation but also introduce students to the underlying explanatory concepts they must master. Normally, for example, the density of concrete objects is not directly observable; students must infer it from their knowledge of weight and size. Though the concept is typically introduced in junior high school, most students attain only rote learning, even into the high school years. Models invented by the Weight/Density and Heat/Temperature Projects attempt to make such unobservable aspects of natural phenomena visible, enabling students, for example, to "see" density depicted visually in a model and thus to develop their own mental models of the distinction and relationship between weight and density. Similarly, the Heat/Temperature simulations help students to develop mental models of the molecular activity associated with heat transfer and other thermal concepts.

The Nature of Science Project conducts research on students' ideas about the nature and purpose of scientific inquiry and on the development of teaching approaches and materials that help students to not only acquire the skills needed for scientific experimentation but also to understand the role of such experimentation in the extension of our knowledge of the natural world. In Year 5, this group has collaborated with the Weight/Density and Heat/Temperature Projects, using these phenomena to investigate students' understanding of models and of the role models play in building scientific knowledge.

Although the Nature of Science Project experimented with the use of published software and the ETC-produced videodisc *Seeing the Unseen*, the group has thus far concluded that a technological component is not essential to its teaching approach. Unlike the other science projects, which find the computer well-suited to the presentation of models of scientific concepts and phenomena, the Nature of Science Group seeks to teach students about the *motivation* for conducting scientific inquiry. To date, the group has neither found nor invented software that communicates that motivation effectively.

Taken together, these three projects provide considerable insight into questions of what computers can and cannot offer in science education. Each group has tested its prototype materials in classrooms, gleaning information not only on their effectiveness but also on their real-world feasibility. This experience sheds light on issues of software design and on related pedagogic decisions about integrating the use of computer models with traditional hands-on activities and integrating the resultant approaches into the regular curriculum and school day. Feedback from teachers who have used the prototype materials has enabled researchers to make well-informed revisions, with the goal of making the materials as useful and flexible as possible in regular classroom settings.

WEIGHT AND DENSITY

Carol Smith, University of Massachusetts, Boston, Project Leader
Micheline Frenette, ETC
Joel Giampa, West Marshall School, Watertown, Massachusetts
Lorraine Grosslight, ETC
Grace Marie LeBlanc, West Marshall School, Watertown, Massachusetts
William Radomski, Newton Education Center, Newton, Massachusetts
Judah L. Schwartz, ETC/Massachusetts Institute of Technology
Sandra Smith, Hosmer East School, Watertown, Massachusetts
Joseph Snir, ETC/University of Haifa, Israel

This project seeks to help elementary and junior high school students learn the distinction between weight and density. The group has developed interactive computer-based models that depict weight, density, and volume in visually quantifiable ways and has examined both the effectiveness of these models in promoting conceptual change among students and the pedagogical issues attendant to the design and use of computer models in science teaching.

The notion of the density of materials is in many ways a conceptual watershed in the pre-college science curriculum. The concept of density is first broached informally in the elementary science curriculum with experiments on sinking and floating, and then more formally in earth science units in the seventh and eighth grades. It is the first topic in the science curriculum which requires students to contrast extensive physical quantities like weight and volume (quantities that vary with the amount of material and combine by adding) with an intensive physical quantity like density (a quantity that is does not vary with the amount of a given material, is defined locally, and combines by averaging). It is also the first intensive physical quantity students encounter that can be understood in terms of an underlying model, the particulate theory of matter. Thus, successful mastery of the distinction between weight and density is not only a conceptual prerequisite for understanding the periodic table and more advanced topics in high school chemistry, biology, and physics, but also can be a foundation for mastery of other more complex extensive and intensive quantities, such as heat and temperature, that students will encounter later in the science curriculum.

Recent work in science education has revealed that most students fail to achieve a conceptual understanding of the topics they are taught in science (Osborne & Wittrock, 1983). This is true for the concepts of weight and density, as well as for the concepts of force, velocity, electricity, and heat and temperature. It is now commonly accepted that one important reason for students' difficulties is that they come to science class with alternative ways of conceptualizing the phenomena they are studying. Thus, science education must confront the difficult problem of teaching in a way that brings about conceptual change.

Traditional ways of teaching science may actually encourage students toward rote learning rather than conceptual restructuring, thus impeding the process of conceptual change. Two characteristics of traditional approaches to teaching have been singled out for criticism: (1) overwhelming students with new vocabulary, defined precisely (from the scientist's viewpoint) but lacking meaning for students; and (2) stressing correct application of quantitative formulas in problem solving rather than encouraging students first to engage in qualitative conceptual analysis of the problem. Indeed, recent research shows that experts engage in a qualitative analysis of a problem before selecting appropriate formulas, so instruction that overlooks this qualitative conceptual analysis overlooks teaching an important part of the expert's understanding.

The ETC Weight and Density Project has sought to teach students about weight and density in a way that actively promotes conceptual understanding. The group believes that asking students to develop their own models to represent these concepts, or to work with models developed by others, is a good way to help them "see" their ideas and engage in conceptual analysis. Thus, they have emphasized engaging students in qualitative conceptual analysis (particularly through modeling activities) before introducing them to quantitative formulas. Indeed, they find that many students invent the formulas themselves from work with modeling activities.

In addition, the group has taken pains to teach in a way that takes into account students' existing conceptions. Present scientific frameworks have developed over hundred of years and are far removed from students' starting conceptions. Like scientists, students need to develop scientific conceptions in stages, not be overwhelmed with the full complexity all at once. Admittedly, identifying "appropriate" intermediate conceptions is a tricky business and calls for careful analysis of the desired endpoint as well as empirical work on students' abilities to make the transitions from intermediate to more advanced conceptions. In the search for intermediate conceptions regarding weight and density, this group has found it useful to examine the work of historically earlier experts — such as Archimedes and Galileo — who contributed greatly to our understanding of sinking and floating, weight and density. Carefully chosen historical expert systems, the group believes, can help educators identify a powerful set of ideas which are within students' grasp and can help students move from their frameworks toward the experts'.

Analysis of the Endpoint: What Should We Expect Students to Learn?

Given the intuitive recognition that objects are made of materials and that a single object can be composed of one or several different materials, one can begin to devise ways to characterize what is distinctive about kinds of materials. Schemes of characterization can be based on macroscopic properties of the substance or on microscopic properties. The notion of density of materials can be approached on either level.

One way to define the density of materials on a macroscopic level is to define a *procedure* to compare the density of two objects. This is the kind of definition of density used by Galileo, who noted two ways that one object can be heavier than another: in absolute weight and in specific weight. When one object is heavier than another regardless of the objects' sizes, the objects differ in absolute weight. Galileo introduced the term "specific weight" to refer to the situation when both objects are the same size but one is heavier. Specific weight, then, describes the kind of heaviness intrinsic to different materials.

The contemporary physicists' conception of density differs from Galileo's notion of specific weight in several important respects. Whereas Galileo defined specific weight by giving a procedure for determining which of two objects is denser, the contemporary definition of density provides an abstract mathematical formulation (divide mass by volume) for quantifying the density of a single object. The contemporary understanding uses the concept not of weight, but of mass, a notion that was not available to Galileo. Within the contemporary framework of physicists, weight is no longer a property of the object or the material it is made from, but is the force of gravity applied to the object (or amount of material) because it has mass. However, since the weight applied to all objects on earth is in direct constant proportion to their mass, one can see the weight of an object as a measure of its mass. Thus, under certain predefined conditions, the distinction between weight and mass is not critical.

In their teaching efforts, the Weight and Density Group's goal is to have students characterize materials at the macroscopic level and, like Galileo, to make a clear distinction between absolute weight and specific weight (which they call density). They go beyond Galileo, however, in giving students' not only a qualitative procedural definition of density, but also a (macroscopic) model and a more formal mathematical definition.

Analysis of Students' Starting Points

Previous research indicates that seventh- through ninth-grade students have considerable difficulty with the concept of density (Rowell and Dawson, 1977a, 1977b, 1983; Hewson, 1982; Piaget and Inhelder, 1974; Inhelder and Piaget, 1958) and provides two major kinds of explanations as to why this is true. First, density is a difficult concept for students because of its ratio structure (density is formally defined as mass per unit volume). Piaget, among others, has argued that the construction of a concept of density depends upon the child's having a schema for ratios and the ability to understand proportional reasoning, two abilities which he claims emerge only in the stage of formal operational reasoning. More recent research suggests qualifications to this view and more optimistic prospects for teaching students about density. Quintero (1980) has shown that ratio reasoning does not emerge all at once. In particular, students begin in the fourth and fifth grades to understand certain intensive quantities defined as ratios. She finds that intensive quantities that have easily visualizable referents (like candies per bag) are more easily grasped by students than those that do not.

Second, density is a difficult concept because students hold alternative conceptions that block their understanding of weight and density as distinct quantities. Thus, to develop a concept of density students must make difficult conceptual changes. Recent research by Smith, Carey, and Wiser (1985) has begun to characterize these fundamental changes. They argue that the core of young children's concept of weight is the notion of *felt weight* and that this concept includes some components that are precursors of a concept of density (e.g., *heavy for size*) as well as some that will remain part of a concept of weight (e.g., *absolutely heavy*). It makes sense for students to unite these two components in one concept because an object's felt weight is a function of its density as well as its absolute weight, and because the notion of how heavy something feels is an inherently comparative one. It is not clear a priori that the relativization *heavy for size* is different in principle from other relativizations such as *heavy for me* or *heavy for objects of its type*. Thus, developing a concept of density involves conceptual differentiations (differentiating weight and density, and mass and weight) as well as restructuring the core of weight (and mass) in terms of a theory of matter.

There is reason to believe that some children begin spontaneously to differentiate between weight and density during the late elementary school years at about the same time they are restructuring their concept of weight (they do not yet distinguish weight and mass) in terms of a theory of matter (Smith et al., 1985). This new concept of density appears to be a qualitative one, however, heavily tied to their concept of material kind. At most, they have a procedural definition for density (they know steel is a heavier kind of material than aluminum, because a piece of steel of a given size is heavier than a piece of aluminum of the same size) rather than a formal mathematical one (weight per unit volume) Indeed, most students are familiar with standard units of weight but much less familiar with standard units of volume. Further, students know little about thermal expansion (Strauss et al., 1983) and hence are not aware of the conditions under which the density of materials may change. Thus, they typically think of density as an invariant property of material kinds rather than an abstract quantity expressing weight/size relationships.

The goals of the curriculum devised by the Weight and Density Group are to encourage students to analyze the weight of objects in terms of a theory of matter (i.e., to see weight as a function of both the amount of material and the density of the kind of material) and to have them see the need for articulating weight and density as two distinct concepts within such a theory. The group wants students to use their qualitative concept of density to understand phenomena, such as sinking and floating. They also want them to go beyond seeing density as an invariant characteristic of material kinds defined solely by a comparative procedure, to understanding a mathematical formulation in which density is defined more abstractly in terms of weight/size relationships. (Note: the group did not aim to have students distinguish mass and weight or tackle the difficult problem of the particulate nature of matter).

The Evolution of the Models and the Curriculum

Pilot Studies (Years 1 and 2)

As a first step in its research, the Weight and Density Group decided to test a basic premise of its approach: namely, that students can more readily understand and quantify intensive quantities that are visually observable than those that must be inferred. To test this premise, the group developed two computer programs, each with slightly different visual analogs for size, weight, and density. In the first program, the computer displays consisted of arrays of dots of two different densities. Objects made of arrays of green dots had a dot density four times that of objects made of purple dots. Thus, the green arrays represented an object made of a material four times as dense as the purple arrays. The weight of an object was represented by the total number of dots in a shape, and the size of an object was represented by the area of the rectangle (see Figure 1). In the second program, the computer displays consisted of arrays of same-colored dots contained in rectangles of two different colors. The red shapes always contained one dot at each intersection of an imaginary matrix, whereas green shapes contained a little cluster of three dots at each intersection of the corresponding imaginary matrix. As before, the total number of dots corresponded to the weight of the object and the area of the rectangle to the volume of the object (see Figure 2).

The programs made it possible to show colored outlines of objects without the dots. After learning which color shape had the higher dot density, students could be asked to predict, from outline color and rectangular area, whether two objects would have the same number of dots. In this way, students had to use knowledge of two variables in the system (dot density and area) to predict a third (total number of dots). Similar problems were constructed for real world materials such as objects made of steel and aluminum.

Taken together, these pilot studies revealed that many children of all ages (second through sixth grade) used different reasoning strategies when dealing with the concrete computer analogs than they did when dealing with the real world materials. In particular, students treated density — dot density in the computer displays — as an explicit quantity and made inferences about how much denser one kind of material was than another. In contrast, students did not infer how much denser steel was than aluminum. Instead, they reasoned much more qualitatively, using either the concept of "heaviness" or "heaviness of kind of material." The group concluded that visual models were helpful in getting students to regard density as an intensive *quantity* in its own right. They further concluded that models should represent all three quantities — size, weight, and density — discretely, to help students' make the correct quantitative inferences.

Designing a Basic Model and Developing a Simulation (Year 3)

Once the group's basic premise had been confirmed, the next step was to design a model and simulation that would be pedagogically useful in an actual teaching situation.

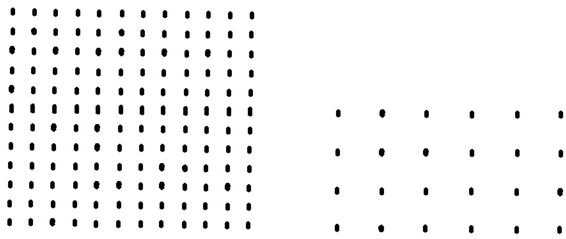


Figure 1

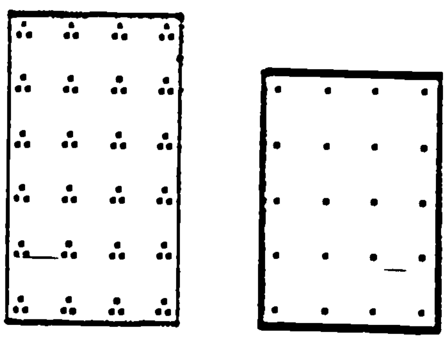


Figure 2

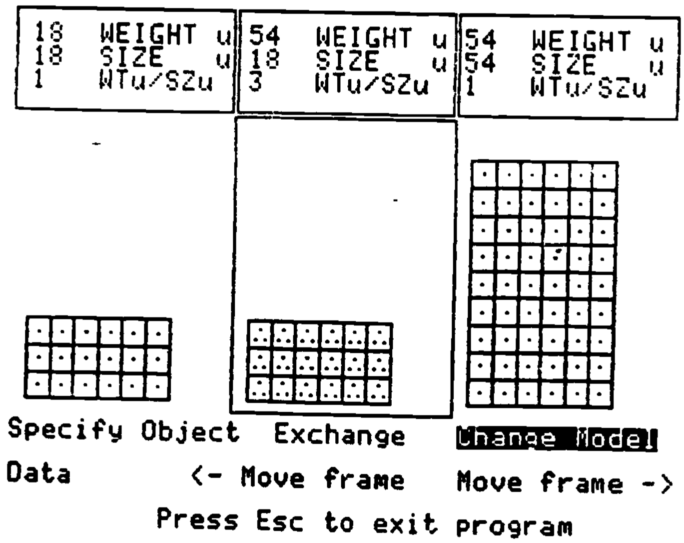
Such a model should be not only precise and valid but also transparent to students. Based on previous research and on the group's own analysis of the desired endpoint for students of this age, they decided that models based on an atomistic theory of matter were too complex to serve as a first model for weight and density. Consequently, they did not make the visual entities (e.g., dots) correspond to subatomic particles like protons and neutrons. Rather, they made the visual entities in the model correspond to abstract attributes — weight and size — of objects, not the objects themselves. By assigning accessible analogs to each of these attributes (boxes for size units, dots for weight units), they created a visual referent for density as well (dots per box). One advantage of making density "visible" using a conceptual model rather than a microscopic model is that the attributes of weight and size are immediately accessible to students in this age range, while the notions of atoms and protons are not.

The programs the group devised allow students to shift between two different visual representations of an object: a pictorial representation and a more conceptual representation. In the pictorial representation, the object is shown in outline and shaded with a color to indicate the kind of material it is made of. In the conceptual representation, the attributes of size, weight, and density become visible through the grid and dots model. In addition to these two kinds of visual depiction of the objects, students can request numerical data about the size and weight of the object and the density of the material (see Figure 3 for examples of these three representations).

The group also developed programs to allow students to manipulate the models in a variety of ways. They can build up to three objects of different size, shape, and material kind, switch between pictorial and conceptual representations (models), request data about the objects they have built, modify the objects, and order them on the screen. Further, they can do simulations of sinking and floating experiments in which they can view the object and the liquid either pictorially or conceptually. They can discover that whether an object sinks or floats depends upon the relative densities of the objects and liquids, and that the level at which a floating object floats is the ratio of its density to the density of the liquid. A distinctive feature of the group's sink/float simulation is that the two physical laws governing sinking/floating (one concerning conservation of matter, the other concerning the equilibrium of hydrostatic pressure) were built into the code of the underlying program.

Developing a Curriculum Using Computer-based Models (Year 3)

Once these initial models and simulations had been developed, the group worked one-on-one with a small number of fourth- through sixth-grade students to refine existing ideas about how to embed the use of these models in a curriculum. This pilot work had revealed that students construct some models spontaneously, although these models reflect their conceptual limitations and difficulties in understanding the distinction between weight and density (and their lack of understanding of atomism). Further, having found that students can engage in metaconceptual discussion about the kinds of representation found in maps, the group concluded that students discussion of maps and of their own models would be a good way of initiating metaconceptual disucssion of models in general. The pilot work had also confirmed that students were, for the most part, able to understand the basic interpretation of the model and to use it to solve quantitative problems. Not surprisingly,


18 WEIGHT u
18 SIZE u
1 WTu/SZu
54 WEIGHT u
18 SIZE u
3 WTu/SZu
54 WEIGHT u
54 SIZE u
1 WTu/SZu
Specify Object Data
Exchange
Change Model
<- Move frame
Move frame ->
Press Esc to exit program

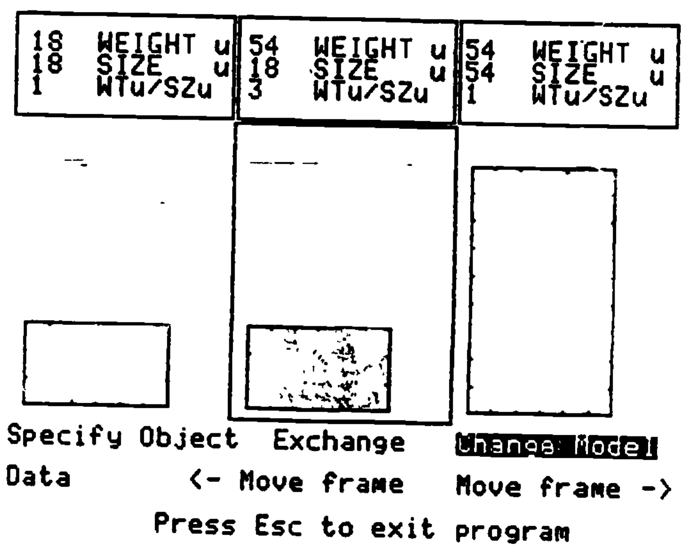

18 WEIGHT u
18 SIZE u
1 WTu/SZu
54 WEIGHT u
18 SIZE u
3 WTu/SZu
54 WEIGHT u
54 SIZE u
1 WTu/SZu
Specify Object Data
Exchange
Change Model
<- Move frame
Move frame ->
Press Esc to exit program

Figure 3

sixth graders were much more facile at solving such problems than fourth graders (who are just learning about multiplication and division).

Finally, the pilot work was helpful in revealing that despite the model's quantitative potential, most students initially interpret it only qualitatively (e.g., they think that a substance that has four dots per box is *more* dense than a substance with two dots per box, but not necessarily *twice* as dense). Further, the group found (as had previous researchers) that the ability to solve solely quantitative problems was not indicative of conceptual understanding. Taken together, these two aspects of the pilot results suggested the need for extensive qualitative activities with the model before moving to activities which encourage students to think more quantitatively. Given that a focus of the group's unit was to lead students toward a more quantitative understanding of density (in the process of making the differentiation), they decided to begin the teaching intervention with sixth graders, who possessed greater mathematical facility.

The First Teaching Study (Year 3)

Using what they had learned in the pilot study, the group developed a curriculum for introducing students to the concept of the density of materials. Important features of this curriculum, designed for sixth-grade students, were: (1) building on strengths in students' initial conceptions as well as challenging them with puzzling phenomena they were ready to understand; (2) integrating work with computer simulations and work with real world materials; (3) emphasizing models, through the use of both student-generated and computer-based models; (4) including metaconceptual discussion with students about the nature of models; and (5) emphasizing qualitative conceptual analysis using models before introducing quantitative formulas. The lessons and activities focused on the size/weight relations of objects made of different materials, the prediction of flotation and sinking, and the prediction of level of submergence. In all the teaching involved eight class sessions.

Students were given a clinical interview before and after the teaching intervention to determine their conceptual understanding. This interview had them order objects by weight and density, explain the basis for their orderings, make models depicting size, weight, and density relationships, and make predictions about sinking and floating.

At the start of the study only one or two students made any differentiation between weight and density. In keeping with their lack of a clear concept of density, students also were unable to formulate a consistent predictive rule about sinking and floating.

After the teaching intervention, the majority of the students were able to distinguish between weight and density and to use the computer model to show and explain the distinction. Many of these children were also able to make consistent predictions about sinking and floating.

Thus, the teaching intervention appeared to help many students make a beginning differentiation of weight from density. (This interview did not include tasks that would determine the extent to which they abstracted the concept of density from material kind.) Students were especially enthusiastic about the sinking/floating unit (although we were able to devote only one or two days to this topic). The group decided to modify this initial unit on density to pay much more attention to the phenomena of sinking and floating.

The Second Teaching Study (Year 4)

In Year 4 the group conducted a more extensive teaching study. They revised and extended the curriculum (from one unit to three), which entailed revising and extending the software as well. In addition, they revised the clinical interview to cover more phenomena and topics and developed a supplementary written pre/post test. The study was conducted in two classes (one sixth grade and one seventh grade).

More specifically, the group restructured the first teaching unit to put much more emphasis on the phenomena of sinking and floating. Thus, the unit began by exploring these phenomena and asking students what factors they thought relevant. The curriculum then introduced the idea of modeling as a way of understanding and clarifying ideas. Students were first asked to model their own ideas and then were introduced to the computer model. They worked with the computer model to formulate a more precise rule for sinking and floating, then went back to working with real world materials and trying to model specific materials. Students ended this first unit by developing a formula to express the interrelations among size, weight, and density.

The second unit focused on changes in the density of materials during thermal expansion. In Unit 1, students always work with situations where density and kind of material covary: the same materials always have the same density; different materials always have different densities. The purpose of Unit 2 was to show students that the density of a given material changes with thermal expansion. Researchers expected that confronting students with the phenomena of thermal expansion would force them to develop a more abstract definition of density in terms of weight /size relationships.

Finally, the third unit introduces the concept of the average density of objects made of mixed materials. Students were shown, for example, how combining an object that sinks with one that floats (in the right proportions) can result in a heavier object that floats. Students were also able to work with a new computer program that allowed them to create a hole in the middle of a sinking object. The size of the hole is fixed, but the size of the object and its material can vary. The density of the liquid the object is immersed in can also vary. The challenge is to figure out the conditions under which the object will float and to formulate a general rule.

Approximately half the students in the sample were given pre- and post-clinical interviews. The clinical interview prior to teaching revealed that only one or two students had a concept of density sufficiently abstracted from material kind to allow them to understand the phenomenon of thermal expansion. Most students had an undifferentiated weight/density concept, while others were beginning to make an initial qualitative differentiation between weight and density. After the first unit, the majority of students made a beginning differentiation between weight and density but their understanding continued to rest heavily on their concept of material kind. After the second unit on thermal expansion, the majority of students showed a more abstract and quantitative understanding of density, as indicated by their success with the phenomena of thermal expansion.

Significantly, students responded consistently across a variety of tasks, suggesting a fairly integrated conceptual understanding.

All the children in the sample who had been given a clinical interview were also given a written test. Although the group found the written test to be less sensitive than the clinical interview in revealing students ways of conceptualizing phenomena, the same general picture of the nature of the conceptual changes emerged from both sources.

Approximately half the class received only the written test (without the clinical interview). Somewhat to the group's surprise, those students who received only the written test had a somewhat different pattern of change than those who had both the clinical interview and written test. The children who were not interviewed responded less consistently from one problem to the other on the written test, and they showed a less well integrated concept of density. Further, they progressed more slowly, never fully catching up with the students who had clinical interviews. Researchers suspect that the experience of the initial clinical interview "prepared" students to respond to the teaching more effectively, while the post-intervention interview helped them consolidate their new understanding. On the other hand, the interviews may simply have engaged students more actively in the process of testing their understanding.

Classroom Trials (Year 5)

During the fifth year of the project, a regular classroom teacher taught the entire Weight/Density Curriculum to all four of her seventh-grade classes. This teacher was highly familiar with the unit (she was a member of the Weight/Density Research Group and had participated in a study done with one of her seventh-grade classes the year before). Nonetheless, this was the first time that a regular classroom teacher (rather than a research assistant) taught the unit.

This study had two purposes. One was to learn more about the feasibility of the unit in regular classroom situations, thus contributing to the development of the curriculum. The second purpose was to learn more about students' initial metaconceptual understandings about models and to determine whether their conceptions of models changed as a result of the unit.

A clinical interview, developed to assess student's conceptions about models, was administered to all students before and after the teaching. The data from the initial interviews has now been analyzed for purposes of developing an initial scoring system. Three levels of understanding of models have been identified, which parallel in important ways the three levels of understanding the nature of science developed by the ETC Nature of Science Research Group. In keeping with the results of the Nature of Science Group, most students begin with a Level 1 or Level 2 understanding.[1] The next step in data analysis will

1 At Level 1, students conceptualize models as miniaturized or direct copies of reality. At Level 2, they begin to see the influence of the modeler's role; they see that models may be constructed differently according to their purposes (e.g., making a particular body system visible so that it can be studied) but still believe the models to convey an objective "truth." At Level 3, students acknowledge that ideas about reality play a role

be to determine the extent to which the students' conceptions of models changed as a result of the curriculum. Given the limited nature of the metaconceptual instruction in the current curriculum, the group expects only limited change. If in the future, however, students were exposed to a series of units which stressed the constructive nature of science, more change in their general conceptions about science could be expected.

The study was very helpful in revealing strengths and limitations of the curriculum from a teacher's perspective. The teacher of the unit was comfortable with (and enthusiastic about) taking a modeling approach to teaching about density and having students work with multiple models, both student-generated and computer-based. After students had extensive experience with the computer-based dots model, she introduced another more numerically based model, which she called the materials model. She also extended our metaconceptual discussion of maps by having students do map-making and then reflect on the choices they made as they constructed their maps. The order of the curriculum units was changed in this study: the unit on average density became Unit 2 and preceeded the unit on thermal expansion. This change "felt right," since the unit on average density continued the discussion of sinking ard floating and at the same time provided motivation for thinking more quantitatively about density. Thus, it was a good sequel to the more qualitative introduction to density stressed in Unit 1. The unit on thermal expansion then came at the end, a change that made sense in light of the previous year's finding that it was the hardest unit for students to grasp.

At the same time, the teacher's discomfort with some aspects of the curriculum and software alerted the group to the need for further changes. As a science teacher, she was uncomfortable working with children's intuitive concept of weight in the model. Her students had been introduced to the notion of mass, and she felt it would be better to use that word instead. (In fact, children's intuitive notion of weight is in some ways closer to the physicist's notion of mass than to the physicist's notion of weight, although it is not equivalent to either). The group decided that exact terminology was a judgment call on the part of the teacher, who was familiar with the curriculum students had already encountered. They decided to build an additional option into the software, allowing teachers to choose the names they want to use for the three quantities in the model (e.g., they can choose to call a dot either a mass unit or a weight unit and the number of dots per box either density or specific weight). Additionally, the teacher was uncomfortable performing some of the demonstrations suggested in the thermal expansion section (she considered them too dangerous) and omitted them. Again, the group decided to include some of the demonstrations as resource ideas and to let teachers decide which ones to use.

Results from this study showed that the majority of students clearly benefitted from the curriculum. Nevertheless, approximately one third of students were unable to develop a differentiated concept of density as a result of the curriculum. From classroom interactions, the teacher in this study sensed that these students were confused about the basic interpretation of the model in terms of the variables of size, weight, and density. The most

---

in the construction of models and that manipulation of models can serve to inform their ideas about phenomena.

salient variable in the model for these students seemed to be number of dots per box, which they mapped onto their undifferentiated weight/density concept. Thus, they seemed content to interpret number of dots per box as both the total weight and total density.

Why should students have this difficulty in interpreting the model? Of course, students who have an undifferentiated concept of weight/density would be likely to make some initial misinterpretations of the sort observed. If, however, the curriculum has the potential to help students make the differentiation, then they would be expected to move toward a correct interpretation of the model by the end of the unit. Many students were able to do this, but some were not, and the group sought to understand the difference. Particularly, the group wanted to determine what fault, if any, lay in the curriculum itself.

Clear answers to these questions have not yet emerged, but clues from the data have led the group to formulate three contrasting hypotheses to pursue in the next few years. The first clue is that the students who have the most difficulty interpreting the model are the ones who show the most primitive understanding of weight/density on the pretest (a few do not even have inklings of the notion of heavy for size). This result contrasts with what Wiser et al. found in their study of heat and temperature among honors eleventh graders; in that study, a student's beginning level of understanding was not predictive of ultimate outcome. Students who failed completely to differentiate heat from temperature on the pretest were able to make a differentiation once they succeeded in internalizing the model. Like the weight/density researchers, however, Wiser notes that some students initially failed to see that the model embodies two distinct quantities, and, as in the weight/density study, the quantity that is hardest for students to grasp as a distinct quantity is the extensive one — total number of dots. Wiser reports, however, that when students repeatedly explore phenomena whose explanation requires them to use each quantity separately, they come to see that heat is in fact a separate variable. This suggests a possible problem in the weight/density curriculum: its developers had assumed the problematic concept to be density, not weight; consequently, most of the phenomena explored (sinking/floating) call for students to think about density. If, however, students have difficulty thinking of total number of dots as a variable distinct from number of dots per box, it may help them to explore some phenomena where weight, not density, is the relevant variable — for example, to explore predictive rules about what objects would make a given bridge collapse. Thus, in order for students to make a differentiation, they need to realize that different variables are relevant in different contexts; it may not be sufficient for the curriculum to emphasize what is perceived to be the weaker concept.

Two additional explanations for students' failure to benefit from the curriculum need to be considered. Both have more to do with the design of the model itself. First, Wiser's model of heat and temperature was more qualitative visually than the model of weight and density developed by this group: that is, Wiser's model used random dot arrangements of differing crowdedness rather than regular numbers of dots per box. This may prevent children from moving immediately to quantitative descriptions of the quantities--instead they may think more in terms of the contrast between dot crowdedness and total number of dots. There are, of course, clear benefits to the weight/density model in allowing students to work out the quantitative formula for themselves. Perhaps the important point is to make sure students perceive the initial variable as a measure of dot crowdedness and not the total number of dots in an object. Second, the students in the study of heat and temperature were honors eleventh graders while the students in the weight/density study were a heterogeneous group of seventh graders. Of interest is the possibility of developmental differences in understanding visually accessible intensive quantities. If such differences exist, then some children may need more time to experiment with the quantities in the model system. These differences in the "transparency" of the model may disappear by a later age. In keeping with this hypothesis, the work of Quintero documents the difficulty many older elementary school children have grasping many simple intensive quantities.

Overall Conclusions and Directions for Further Research

Overall the group concludes that there is much promise in teaching students about density using a modeling approach. One of the potential benefits is that this approach helps students build a firm qualitative understanding of density and of the ways it is distinct from weight, that is, the approach promotes conceptual understanding and not just rote learning of formulas. Another potential benefit is that students begin to learn about the nature and uses of models as tools for thinking.

Studies to date have shown that the group's curriculum has helped many sixth- and seventh-grade students to differentiate between weight and density. The curriculum's lack of success with some students is a matter for further study. Nonetheless, its effectiveness is impressive when one considers that other approaches to teaching ab t density have reported no success at all with students in this age group (Cole, 1968).

The process of developing/evaluating its materials has led the group to clarify its ideas about the design of software and curriculum to promote conceptual change and to revise its curriculum and sofware accordingly. For example, the group now believes that in order for students to grasp the idea that weight and density are distinct variables, they need to explore situations in which the manipulation of the weight variable and the density variable produce decidedly different effects. Therefore, in addition to sinking/floating experiments where material density is the relevant factor, the group is now adding a simulation to the software that allows students to discover and explore the variable (weight) which is relevant to the collapsing of bridges and platforms of varying strength. These two computer simulations will be combined within one game framework in which students manipulate relevant vairables in order to move objects through a maze containing various liquids and platforms bridges. The level of difficulty of this game can be conrolled somewhat to provide for individual differences. For example, an easy situation would require a student to know which of several objects would float in a given liquid, whereas a more difficult problem would invoke the student's knowledge of the objects' levels of submergence. Experiments with styrofoam bridges similar to those performed in the computer encironment will be included in the classroom activities as well.

The group continues to provide activities which enable students to evaluate and reflect on their experiences with real materials through the use of explicit conceptual models. The group now believes that students benefit from being able to switch the computer's display back and forth between conceptual and pictorial representations, allowing them to link observable phenomena more fluently to the scientific explanations of those phenomena. (For further discussion of the use of pictorial and conceptual representations, as well as other issues in simuation design, see *Not the Whole Truth: An Essay on Building Conceptually Enhanced Computer Simulations for Concept Learning*, Snir et al. [1988]). Two further plans for development are related to this consideration. First, students will be more motivated to use conceptual representations if the computer activities require them to use those representations to effect or predict the behavior of realistically represented objects. For example, a lesson might require students to construct objects that will behave in some observable way (e.g., float at at given level or sink a boat), with the information needed to construct such an object obtainable only by using the conceptual representation. Second, the conceptual environment itself will be enriched and expanded. In response to indications that the model's primitive "total number of dots" (i.e., weight) is less perceptually salient to students than the primitive "dots per box" (i.e., density), the group plans to increase students' options for exploring the weight variable. Currently student can change only the size and material of objects directly; any changes in weight are the result of the manipulation of these other variables. The group now plans to let students directly add or subtract weight units in a separate window and then witneess their distribution in an object as density.

Once these changes are made, the group plans to pursue two research questions. The first question concerns the role of models in facilitating conceptual change. This study will put the curriculum to the test, contrasting its effectiveness with the best hands-on curricula the group can develop to cover the same topics without the use of models to summarize and clarify ideas. The second question concerns the role of metaconceptual understanding in facilitating conceptual change. Here the central question is whether students with a more constructivist epistemology are better able to make conceptual changes using the curriculum than those who believe that knowledge is a direct "copy" of reality.

HEAT AND TEMPERATURE

Marianne Wiser, Clark University, Project Leader
Stephen Cremer, Braintree High School, Braintree, Massachusetts
Walter Engstrom, Braintree High School, Braintree, Massachusetts
Lorraine Grosslight, ETC
Liana Halkiadakis, ETC
Daphna Kipman, ETC
Lee McKenzie, Clark University
Judah L. Schwartz, ETC/Massachusetts Institute of Technology
Chris Unger, ETC

For the past five years, the research of the ETC Heat and Temperature Project has focused on high school students' understanding of basic thermal physics, particularly the difference between heat and temperature. The group has investigated the source(s) of students' difficulties and designed software and teaching materials to alleviate those difficulties. Using computers first as instruments to collect and display data and to simulate laboratory experiments, then later to present models that explicate the difference and relation between heat and temperature as well as other thermal concepts, the group has explored the pedagogical potential of computer-based conceptual models to help students make difficult conceptual reorganizations.

The Heat/Temperature Group views learning as the interaction between (1) the information about a domain of knowledge presented in lessons and textbooks and (2) the internal mental state of the student (i.e., the student's pre-existing knowledge about that domain). Driver and Erikson (1983) refer to such preconceptions as "alternative frameworks" because they are different from the theory to be learned. These alternative frameworks are difficult to displace for two reasons. First, alternative frameworks possess a familiarity and intuitive appeal that is generally lacking in textbook theories. Second, the alternative frameworks may include inappropriate concepts, rules, and explanatory schemata that interfere with students' interpretation of textbook theories and statements. The group believes that learning basic thermal physics is particularly hard because students must undergo a complete conceptual reorganization.

Since its inception, the Heat and Temperature Group has had three interrelated goals: to characterize students' initial state (i.e., the ideas and concepts students develop on their own and bring to the classroom); to develop a microcomputer-based curriculum to address these preconceptions and promote reconceptualization; and to monitor the resultant interaction between the students and the curriculum. This is a recursive process: by watching students in the classroom and evaluating the effects of their teaching interventions, researchers update their characterization of students' conceptions and modify the curriculum accordingly.

Students' Conceptualization of Thermal Phenomena

The following model for students' conceptualization was established through approximately 60 clinical interviews (Wiser, 1985; 1987). Students think of heat as an intensive quality measured with a thermometer: the stronger the heat, the higher the level in the thermometer. Many of them think of heat as having force and actually pushing up the level of the thermometer. They consider cold a separate and opposite entity; like heat, it has force and is measured with a thermometer. Thus, temperature (the thermometer reading) is seen as the synonym of heat, as a superordinate term for both heat and cold, or as the measure of heat and cold. Students conceive of thermal phenomena as produced by sources of heat (or cold) acting on passive recipients ("passive" in the sense that the state of the recipient does not influence heat transfer). Hot sources emit heat spontaneously, applying more or less intense heat, depending on their temperature. Students have *no concept of amount of heat in the extensive sense*. They use the words "amount of heat" only in the sense of heat intensity. They account for extensivity by a causal scheme: larger sources have more effect not because they give off more heat but because they have more contact area with the recipient, applying their heat to a larger portion of the recipient. A source will also have a greater effect the longer it stays in contact with the recipient. For example, a large amount of boiling water has the same heat as a small amount but will melt more snow because it covers more of the snow or because it stays hot longer or both.

Because students think of sources of heat as communicating *their* heat (i.e., heat of a certain degree or intensity) to recipients, the physicist's notion of fixed points[1] is impossible for them to understand. How could the recipient stay at the same temperature while changing state, since it is receiving heat and therefore increasing in hotness? Students' interpretation of fixed points is consistent with their own framework: the constancy of temperature during phase change is either ignored or interpreted as an absolute limit of the substance. Thermal equilibrium, in the physicist's sense, is also not intelligible because it requires a concept of heat distinct from temperature. Sometimes students can understand that two bodies in contact reach the same temperature, but they do so on the basis of a single thermal concept: the source cannot make the recipient hotter than itself because it is communicating to the recipient heat of a certain degree. Specific heat phenomena are also hard for students to understand: if the same heat is applied to the same amount of two different substances, they reason, the temperature changes should be the same.

Students' concept of heat is clearly undifferentiated with respect to the physicist's concepts of heat and temperature; to students, heat is both intensive — its measure is the same at every point in the source — and extensive — the heat in a larger quantity of hot water has more effect. Like the physicist's heat, the students' heat is transmitted from hot to cold objects and can be generated by chemical reactions. Like temperature, the students' heat is measured with a thermometer, its intensity corresponds to felt hotness, and (at least for some students) it reaches the same level in two objects in contact. The students' concept lacks critical components of both heat and temperature: the notion of amount of heat and a clear understanding of thermal equilibrium.

Microcomputer-Based Laboratory Interventions

The group's inital teaching interventions used microcomputers as laboratory tools, both in the form of Microcomputer-Based Laboratories (MBL) which allow students to collect, display, and summarize data and Laboratory Simulations which allow them to "conduct" on-screen experiments that are impractical to carry out in the real classroom laboratory. The content of the interventions was chosen to challenge students' preconceptions, mostly by demonstrating empirically that temperature does not measure heat and that the quantitative relation between heat and temperature involves other factors such as mass, kind of substance, and whether phase change is taking place. MBL emphasize the difference between heat and temperature during data collection: heat and temperature are measured using different instruments and have different visual representations on the screen. Students use heat pulse generators — heat "dollopers" — to heat and melt substances and thermal probes to record tempearture. The software allows students to dispaly graphs of temperature varying in real time, with each dollop of heat indicated on the screen by an arrow on the temperature graph. Besides giving students direct phenomenological access to a measure of heat independent of temperature (something

1 According to current theory in physics, phase changes (from solid to liquid, liquid to gas, liquid to sold, and gas to liquid) take place at fixed temperatures (for a given pressure), which depend on the substance changing phase. Moreover, the temperature stays constant during the phase change.

traditional laboratory methods do not afford), M[illegible] give them a sense of the extensivity of heat: amount of heat is represented by total number of dollops.

Classroom trials of the Heat/Temperature Group's MBL-based interventions revealed that they were more successful than traditional methods in helping students to learn quantitative probem-solving, most likely because they gave students a working concept of unit of heat (the dollop) which helped them deal with quantitative laws. At the conceptual level, however, the group found no positive effect of MBL compared to traditional teaching. On the one hand, the phenomena students explored in the laboratory and the quantitative laws they were to infer from the data rarely led (in either the MBL or the control group) to the intended reconceptualization, i.e., the differentiation of heat from temperature and the acquisition of the concept of heat in the extensive sense. On the other hand, the laws themselves either were not learned or were learned only as problem-solving procedures; when internalized at all, they were often vague, incomplete, and therefore wrong. Similarly, concepts such as specific heat were either not learned or were misunderstood. Of course, these two aspects of the results are two faces of the same coin: rather than change their existing framework to fit the new information, students attempted to fit the information into their framework, distorting it in the process. Thus, simply challenging the students' beliefs with experimental evidence and encouraging them to infer regularities in their data did not seem to lead to conceptual change. Whatever clarifications MBL enabled at the phenomenological level were insufficient at the conceptual level.

Computer Models of Thermal Phenomena

The goal of the group's present and future work is to facilitate reconceptualization at two levels: at the metaconceptual level, to foster students' awareness of the mental process involved in rejecting one framework for another, while, at the conceptual level, to promote meaningful understanding of the content of the textbook theory (the new framework). When the group's MBL interventions alone failed to achieve these goals, researchers moved toward a different type of intervention. Their new approach retains an MBL component, but its centerpiece is a set of computer models that make the textbook concepts explicit and observable. This phase of the work has focused on content rather than metaconceptual issues, on the assumption that the most important factor in fostering reconceptualization is to render the textbook theory understandable *in spite of the misconceptions* students hold.

The computer models the group has developed represent basic thermal concepts (heat, temperature, and specific heat) and their relations, as well as phenomena such as conduction. To minimize the distortions resulting from misassimilation into the students' framework, the models explicate the concepts at two levels: a macrolevel, which corresponds to the empirical and phenomenological level where variables are apprehended and measured, and a molecular level, where those variables and the laws relating to them find their meaning. This two-level representation makes it possible to sh[illegible] *how* heat and temperature differ, and *why* substances differ in specific heat, not simply *that* they do. It gives students an explanatory framework that can help them relate and integrate pieces of information often treated as separate topics in the traditional curriculum, as well as help them solve problems about these topics. Because the computer models depict concepts rather than phenomena the group calls them conceptual models.

The six computer-based models relate temperature and heat to the amount of mechanical energy in one molecule and in a whole object. HEAT & TEMPERATURE, the main model, illustrates visually the difference between heat and temperature and the quantitative relation of heat, mass, and temperature. In the model, the amount of heat energy in an object is represented on the screen by a discrete number of "energy dots" in a rectangle, each dot representing one unit of heat and the size of the rectangle representing the mass of the object. Consequently temperature is correlated with the density of the energy dots (for a given substance). The VIEW option allows users to view the molecules in motion (the molecules are not displayed on the screen in the normal mode of operation) and thus to verify that higher temperature means faster moving molecules; it also reminds them that the energy dots do not represent molecules. The CONTACT option allows users to observe thermal conduction. A solid bar appears between the two containers to simulate contact, and the energy dots are redistributed, moving from the container at the higher temperature to the one at the lower temperature, until equilibrium is reached. In a second model, ENERGY IN MOLECULES, molecules, represented by open circles containing energy dots, can be made to appear within the rectangle to show that temperature is also correlated with the number of energy dots per molecule and that adding one heat unit to each molecule of an object raises that object's temperature one degree, whatever the mass of the object. A third model, COLLISION, shows students that heat exchange between two bodies at different temperature is really an exchange of mechanical energy during the collision of fast and slow moving molecules. The model "defines" the energy dots as units of mechanical energy by showing that the number of dots in each molecule is proportional to its kinetic energy, and that although dots are exchanged during collision, the total number of dots is conserved.

The concept of specific heat is introduced in a series of three additional models. The KINETIC & INNER ENERGIES model introduces specific heat as a function of molecular complexity. Like COLLISION, it depicts collisions between two molecules, but it takes into account the molecular structures of the molecules and two types of energy, the kinetic energy of the center of mass motion of the molecules and the vibrational and rotational energy inside the molecules (which is called "inner" energy in the program and during classroom interventions). The focus of the model is that the constant ratio between the inner and the kinetic energies is an attribute of a molecule that does not change during collisions. The SPECIFIC GRAM model represents the energy content in one gram of different substances as a function of molecular mass as well as molecular compexity and gives the user a visual definition of specific heat. The SPECIFIC HEAT model is the macrolevel version of SPECIFIC GRAM; it depicts the relation among heat, temperature, specific heat, and mass in different substances, and it includes an energy representation at the molecular level showing that temperature is a measure of the average kinetic energy per molecule.

These conceptual models are tailored to present both explicitly and transparently the particular aspects of the concepts that students' misconceptions make it hard for them to grasp in a traditional curriculum: the extensivity of heat, the differences and relations between heat and temperature, and the nature of heat and specific heat. The spatial properties of the visual representations of heat and temperature are *analogues* of the distinguishing properties of the concepts — i.e., the representation of heat is extensive (total number of dots) and the representation of temperature is intensive (dot density) — and the quantitative relation of heat, mass, and temperature is represented by the spatial relation among their visual representations (total number of dots = rectangle size x dot density). Thus, the difference and the relation between heat and temperature are visually explicit and embodied in the representations. Further, by allowing users to set heat content and temperature independently, the models provide a more flexible environment for understanding the distinction between heat and temperature than real laboratory experiments in which heat transfer is not so easy to control as temperature and cannot be dissociated from it.

By allowing students to move from the representation of phenomena at the macrolevel (e.g., heat input, temperature change) to the interpretation of those phenomena at the molecular level (e.g., change in energy per molecule) within a single display, and by using a single format (energy dot), the models help students understand the nature of the variables and provide an explanatory mechanism for the laws and principles they need to learn. In doing so, the models give these principles a necessity not available at the phenomenological level.

Because the parameters of the models correspond directly to the variables manipulated in experiments and mentioned in problems, the programs can be used easily to model laboratory experiments and to solve problems. Some options represent laboratory activities (e.g., ZAP mimics a hot plate effect and CONTACT can be used to represent the mixing of two quantities of a substance), thereby helping to establish and maintain the link between phenomenological variables and their representations.

Like all model builders, members of this group have struggled with issues of truth and simplicity. They have made some radical simplifications, choosing at times to violate principles dear to physicists in order to represent the aspects of the thermal concepts and laws they consider essential (extensivity of heat versus intensivity of temperature, e.g.) in the clearest way possible. They talk about the heat *in* objects, pretend that all molecules in an object in thermal equilibrium move at the same speed, and, in the main program, present temperature as heat density. Because the models are presented as abstractions, as simplified representations of reality, and because part of the group's teaching approach will be devoted to helping students understand the nature of models, particularly their revisability, they believe the simplifications, however heretical they might look to some experts, will not hurt students and, in fact, will help them by making the basic theory easier to learn. Should some students choose to pursue the study of thermal physics, they will have the mental apparatus necessary to revise their beliefs without a difficult reconceptualization.

Classroom Study

Design and Methods

After establishing in a pilot study (see ETC Technical Report TR88-7, *Can models foster conceptual change? The case of heat and temperature*) that the computer models made sense to subjects untrained in physics and helped them to differentiate between heat and temperature, the Heat/Temperature Group conducted a classroom study among eleventh graders to evaluate the effectiveness of the models compared with a traditional curriculum. The students in both classes were honors science students of equivalent ability. One class was randomly chosen to study a curriculum featuring the computer models (model group; 16 students), while the other class studied the standard heat and temperature curriculum and served as a control (control group; 13 students). The teaching intervention lasted three weeks.

The topics in the curriculum was the same for both groups: nature of heat and temperature, conduction, thermal expansion, quantitative relation of heat, mass, and temperature, phase change, specific and latent heat, absolute zero, mixtures, and the relation between work and heat. Both groups used the same textbook (*Conceptual Physics* by P.G. Hewitt) and performed the same laboratory experiments with MBL software but received different worsheets. In the control group the teaching intervention consisted of a series of lectures focusing on the target concepts, followed by lab experiments and paper-and-pencil exercises. In the model group, lectures were kept to a minimum; students spent most of their time in pairs, performing laboratory experiments on a given topic and then learning the computer model related to that topic. Their worksheets contained detailed instructions for using the software, theoretical information related to each model, descriptions and interpretations of the models, and exercises to be performed while interacting with the computer models. The teacher was available to answer questions.

All students were tested before and after the teaching intervention. They were interviewed individually for about half an hour and took a written test consisting of quantitative problems. The interview was of a conceptual nature, consisting of a series of open-ended, nonquantitative problems that probed students' ideas about the relation between heat and temperature, the nature and measurement of heat and temperature, thermal equilibrium, specific heat, and the mechanism of thermal conduction. Interviewers followed students' answers closely, asking for clarifications, pointing out potential inconsistencies, and encouraging them to express their conceptualization as explicitly as possible.

Results

The quantitative test showed a nonsignificant pre-to-posttest advantage of the model group over the control group. The more interesting and notable effects of the models appeared in the clinical interview data. The analysis presented here is based on interviews with 11 students in each group.

At the conceptual level, the results from the interviews show a much better grasp of the difference between heat and temperature and greater willingness and ability to articulate those differences explicitly among the model students than among the control students. The model students maintained this superiority at the level of qualitative problem solving. More model than control students correctly used the concept of amount of heat and correctly expressed the relation between heat, mass, and temperature. In addition, more of them appealed to thermal equilibrium in the proper contexts and recognized situations in which specific heat played an explanatory role. The model students also had a better grasp than the control students of the molecular mechanisms underlying thermal phenomena. For example, they could explain in molecular terms the contrast between the extensivity of heat and the intensivity of temperature, could explain conduction and thermal equilibrium, and gave excellent molecular accounts of specific heat. Finally, the model students' knowledge was much better integrated than that of the control students. They could use several principles simultaneously to make predictions about novel situations (i.e., situations not discussed in class).

The computer models appear to have helped the poorer as well as the better students. In the model group, some of the best posttests came from students whose pretests showed very strong misconceptions and little knowledge of the textbook theory. In contrast, the pretest and posttest performances of the control group appear more closely linked, i.e., the students who showed strong misconceptions on the pretest appeared to have learned little from the intervention, while those who showed a good grasp of the textbook theory on the posttest were those who aready knew something about it before the intervention.

Conclusions and Directions for Future Research

The conclusions from the classroom study are straightforward. The interviews demonstrate that the computer models helped students understand heat and termperature. Students who used the models displayed a firmer grasp than the control students of the various thermal concepts, laws, and principles, both at the theoretical and applied levels. Their knowledge formed a more integrated whole, and they showed fewer remaining misconceptions.

Neither this study nor the pilot study (see ETC Technical Report TR88–7, *Can models foster conceptual change? The case of heat and temperature*) sought to understand how students came to give up their own beliefs (especially the belief that temperature measures heat) and to adopt the computer model. Thus, the data from these studies do not lend themselves to a systematic analysis of the process of reconceptualization. A tentative sketch of the evolution of students' thinking can nevertheless be drawn from the classroom discussions during this study and the pilot study interviews.

It appears that the students who underwent a conceptual change as a result of using the models first established a purely abstract relation among total number of dots, dot density, and rectangle size in the models. This quickly became an "intermediary" relation of total number of dots, dots per molecule, and mass, and then more slowly, a relation of heat, temperature, and mass. Two major threads lead to final reconceptualization. The first was mapping temperature on dot density. This was relatively easy, because this notion fit well within the students' own framework (denser dots means more dots per molecule, thus more energy per molecule, which they already knew means faster-moving molecules and, therefore, hotter substance). The second thread was the realization that amount of heat is represented by the total number of energy dots, a realization that came more slowly because the students had to adopt a new concept (heat extensivity) which violated their initial belief. In the beginning, they mapped the energy dots onto their undifferentiated concept of heat: the COLLISION program showed them that dots represented energy transmitted from a hotter body to a colder one but did not attempt to establish the differentiation between heat and temperature; they interpreted COLLISIONS as "the dots have something to do with heat." Later, ZAP evoked dolloping, reinforcing the notion that heating was represented by adding more dots. The students had no difficulty understanding that more ZAPs meant more heat and that more ZAPs consisted of more energy dots. At this point, more or less readily, they accepted that amount of heat was represented by the total number of dots. Having already come to believe that temperature was represented by dot density, they were forced to accept that temperature does not measure heat (because dot density and total number of dots are different). Once this mapping was complete, the students adopted the model as a representation of heat and temperature: they had undergone conceptual change.

The differentiation was faciliated by the micro level (molecular) representation; at this level students saw the molecules in the object, each with a certain number of dots, and recognized that raising the temperature involved giving *every* molecule a certain number of extra dots, the total number being proportional to the number of molecules. Relating the total number of dots to the total number of molecules fostered in the students a sense of extensivitiy for heat, because the number of molecules is so obviously extensive. The students' acceptance of the idea that the total number of dots represented amount of heat resolved some paradoxes in their theory and may have contributed to reconceptualization.

In future reasearch, the Heat/Temperature Group wants to pursue the study of the differentiation process and to test and enrich the model outlined above. The group would like to conduct longitudinal studies, in which one or two students at a time are exposed to the computer models under the guidance of a researcher. Tape recording the sessions and keeping track of the students' interactions with the computer would allow researchers to follow in detail the evolution of their thinking.

A second line of research concerns the metaconceptual issues. The group intends to integrate discussions about the nature of models and theories, about students' misconceptions, and about reconceptualization into its curriculum. A third line of research concerns curriculum development which so far has focused mainly on the development of an extensive curriculum for eleventh graders. The group would like to adapt that curriculum for the ninth grade (when thermal physics is generally introduced) and to add new topics, such as latent heat, for which new software will be needed. Finally, the Heat/Temperature Group would like to integrate its models and its curriculum with the ones developed by the ETC Weight /Density Group, especially by developing a teaching unit on the particulate theory of matter.

NATURE OF SCIENCE

Susan Carey, Massachusetts Institute of Technology, Project Leader
Diane Bemis, Watertown High School, Watertown, Massachusetts
Risa Evans, ETC
Mary Greaves, Day Junior High School, Newton, Massachusetts
Maya Honda, ETC
Eileen Jay, ETC
Wayne O'Neil, Massachusetts Institute of Technology
Sandra Smith, Hosmer East School, Watertown, Massachusetts
Chris Unger, ETC
Al Weinstein, Cambridge Rindge & Latin School, Cambridge, Massachusetts

The Nature of Science Project seeks to help junior high school students understand the constructed and fluid nature of scientific knowledge and the inquiry process that supports such knowledge. The group has studied students' understanding of scientific inquiry and has designed a curriculum to teach students not only the methods but also the motives for doing science.

Current educational practice emphasizes the "process skills" involved in constructing scientific knowledge — such diverse skills as observation, classification, measurement, controlled experimentation, and construction of data tables and graphs of experimental results. These skills are typically covered in the junior high school science curriculum, beginning with the introduction of "the scientific method" in the seventh grade. Since students of this age do not spontaneously measure and control variables or systematically record data when they first attempt experimental work, the emphasis on process skills is certainly appropriate. What the standard curriculum fails to address is the motivation for using these skills to construct scientific knowledge. Students are not challenged to employ these process skills to explore, develop, and evaluate their ideas about natural phenomena. Rather, instruction in the skills and methods of science occurs outside the context of genuine inquiry. This is true of the presentation of the scientific method in current junior high school textbooks, standardized tests, and curricular materials (for a detailed discussion, see ETC Progress Report #86-11).

The standard junior high school unit on the scientific method contains many exercises — for example, identifying independent and dependent variables in experiments and identifying poorly designed experiments in which variables have been confounded — to teach students about the design of controlled experiments. Students are not, however, taught the *purpose* of the scientific method, that is, to construct theories to explain nature. They are not asked to think about what makes the effects of some potential variables worth assessing (i.e., controlling and manipulating) and others not. Although students may go on to design and conduct controlled experiments, the possible hypotheses and variables (and thus, the experimental outcomes) for a given problem are often prescribed by the curriculum. Thus, the curriculum fails to teach students that hypothesis formation and testing are always constrained by one's current conceptions of a phenomenon and that in some cases the researcher might not conceptualize the relevant variables. This approach provides no context in which students can learn about the nature of science: that scientific understanding advances when researchers discover variables and construct theories that are useful in describing and explaining the phenomena under investigation (or other seemingly unrelated or unanticipated phenomena).

The work of the Nature of Science Group responds to these deficiencies in the standard curriculum. Eschewing a narrow focus on process skills, the group's research and curriculum development efforts have aimed to help students understand the nature of scientific inquiry within the constructivist view of science. First, the group assessed the conceptions that students bring to the classroom regarding the nature of the scientific enterprise. Next, researchers developed and implemented curricular materials to address students' initial conceptions and introduce them to the constructivist view. Then, they assessed the effectiveness of the curricular intervention in changing the initial conceptions. The group assumes that if students are to gain a better understanding of the nature of science, they must be actively involved in theory building — in constructing and evaluating explanations for natural phenomena — and they must be engaged in metaconceptual reflection on that process.

Years 1 through 3: Development of the Nature of Science Unit and Assessment Measures

During the first three years of the project, the main focus of the group's work was to create a curricular unit that would introduce students to the methods of science by permitting them to "do science," that is, to engage in theory building, albeit on a small scale. The challenge was to find phenomena that were conceptually accessible to investigation and explanation by students. An additional challenge was to create lesson plans and curricular materials that would make feasible the exploration of these phenomena in a regular classroom environment.

Materials were selected and/or developed for pilot testing in four areas: (1) computer-based "puzzle-solving" to introduce hypothesis formation and testing; (2) microcomputer simulations of experiments to introduce experimental method; (3) theory construction in a nonlaboratory setting using natural language phenomena; and (4) theory construction in a laboratory setting using biological and physical phenomena. In Years 1 and 2, the group selected and piloted software and lesson plans on natural language phenomena (for a detailed discussion, see ETC Technical Report TR85-23). In Year 3, the group developed and piloted teaching materials on a phenomenon in biology, the nature of yeast, and a phenomenon in physics, the density of sinking and floating materials (for a detailed discussion, see ETC Progress Report TR86-11).

On the basis of these pilot studies, the group assembled a curricular unit that would engage students in theory building and metaconceptual reflection on the methods and process of scientific inquiry. This unit began with a week of lessons in which the methods of science were introduced using two software packages: *The King's Rule: Mathematics and Discovery* (Sunburst Communications), which covers hypothesis formation and testing; and, *The Scientific Method* (Cygnus Software), which covers experimental method. The core of the unit consisted of two weeks of lessons on the nature of yeast and a week of lessons on linguistics. These two sets of theory building lessons make somewhat different yet complementary points about the nature of science and inquiry. The yeast lessons exemplify the cumulative nature of science, the process by which a series of experiments can lead to a deepening understanding of a natural phenomenon. The linguistics lessons stress other aspects of theory construction, especially the abstraction and justification of new theoretical entities, and the role of counterexamples in testing a theory (for a detailed description of the unit and the actual lesson plans, see ETC Progress Report TR86-11.)

In preparation for a classroom field test of its unit in Year 4, the group also began to devise student assessment measures. Group members reviewed and critiqued available standardized tests designed to assess junior high school students' understanding of scientific inquiry. They then developed a written pre/posttest which included both items adapted from these tests and items they wrote themselves. In addition, they developed and piloted clinical interview questions to assess students' understanding of the nature of scientific work (for a detailed discussion of the development of these measures, see ETC Progress Report TR86-11.)

Year 4: Classroom Studies Using the Nature of Science Unit

During Year 4, the group conducted two classroom studies using the Nature of Science Unit with seventh-grade students. These studies had two major research goals: first, to probe students' initial conceptions of the nature and purpose of science and of the process of scientific inquiry; and second, to explore whether it is possible to move students beyond their initial conceptions using the group's curricular intervention. The two studies are described briefly below (for a complete description of the studies and results, see ETC Technical Report TR88-2).

Study 1: Comparison of the Nature of Science Unit and a Standard Unit

The first field trial of the entire Nature of Science Unit (the experimental unit) compared its effectiveness with that of a well-developed, standard unit (the control unit) designed solely to teach process skills. One of the questions to be answered was whether spending time on the considerable material on the nature of scientific knowledge and inquiry in the ETC unit would lead to a decreased mastery of the process skills that are covered in both units, but are the focus of much more practice in the control unit.

The study involved four seventh-grade science classes. The experimental group (n=38) and the control group (n=38) each consisted of one class in which students were considered average and above-average in ability and a second class in which they were considered average and below-average. The teaching was shared by the regular classroom teachers and a member of the Nature of Science Group, each of whom taught one experimental class and one control class each day. Before and after the intervention, all students were given the written pre/posttest, and a representative sample of students from all classes (n= 14) were also interviewed.

Results. The results of this first trial showed that the ETC Nature of Science Unit was comparable to the standard unit. Analysis of the pre/posttests revealed a modest, statistically significant improvement of 9.4 percent for both the experimental and the control groups ($p < .0001$, paired comparison t-test, 1-tailed). There was no significant difference in the degree of improvement between the groups on either the test items about the nature of science or the items probing the components and logic of experimentation.

Analysis of the interviews allowed the group to develop a coding scheme and to identify and repair shortcomings in the design of the interview which prevented a full characterization of students' conceptions of the nature of science. Given the small number of students interviewed, quantitative analysis of the interviews was pursued merely to gain a rough idea of the level of responses and any strong group differences. All students made some gain; overall, the mean score per item increased significantly from .85 to 1.22 ($p < .01$, Wilcoxon signed ranks test, 1-tailed). Although some group differences on sections of the interview were significant, none was strong.

Classroom observations revealed several problems with the experimental unit. First, the software sequence proved disappointing. Although students enjoyed using the computers, were engaged by the puzzles presented in *The King's Rule*, and seemed to learn certain aspects of hypothesis formation, the software did not explicitly make points the group hoped students would learn about revising hypotheses acccording to evidence or about the search for counterexamples. The *Scientific Method*, although effective in making specific points about experimentation, did not consolidate those points. The group concluded that the same lessons might have been taught more effectively by a teacher. In addition, while the Nature of Science Unit was teachable to whole classes, it required the special conditions of the study — two teachers and an observer always present — to make it so; this was particularly true for the yeast lessons which proved to be logistically cumbersome. Finally, the group found that many of the metaconceptual points about the nature of science were too diffuse and poorly articulated. These issues were addressed in Study 2.

Study 2: A "Real World" Trial of the Revised Nature of Science Unit

One of the main objectives of Study 2 was to obtain a more sensitive assessment of students' initial understanding of the nature of science and any changes following instruction. In order to do this, both the written pre/posttest and the clinical interview were revised to allow a more adequate characterization of students' conceptions and more specific probing of points covered in the unit.

A second objective was to improve the unit based on the findings in Study 1 and to observe its use in a typical classroom situation. To this end, a number of revisions were made, including: (1) addition of an introductory lesson and a final, wrap-up lesson; (2) replacement of the software sequence with lessons using segments from the ETC-produced interactive videodisc, *Seeing the Unseen* , on hypothesis testing and classification schemes (described in detail in ETC Technical Report #87-4); (3) revisions in the yeast lesson plans to make them manageable by an unassisted teacher; and (4) discussion and written exercises integrated throughout the unit to make explicit points about the nature of science and to help students reflect on those points (for a detailed description of the revised lesson plans, see ETC Technical Report #88-2).

The revised Nature of Science Unit was taught in five mixed ability classes ($n= 76$) by the regular teacher. (Due to the teacher's time constraints, the week of linguistics lessons was omitted from this trial.) Before and after the intervention, the revised pre/posttest was administered to all students. In addition, the revised clinical interview was administered individually to randomly selected students (n= 27).

Results. Fifty-nine students completed both the pretest and the posttest and could be included in the pre/posttest comparision. Overall, the pretest mean of 68.5 percent correct increased to a posttest mean of 74.4 percent — a small but significant improvement of 5.9 percentage points ($p < .0005$, paired comparison t-test, 1-tailed). Gains on the six subsections of the written test averaged from 0 to 13.6 percent, with the largest significant improvements in subsections on the Nature of Science and the Development of Ideas ($p < .0005$ and $p < .005$ respectively, paired comparison t-test, 1-tailed). Subsections on Identification of Hypotheses and the Nature and Purpose of Experiments also showed significant improvement (both $p < .05$, paired comparison t-test, 1-tailed).

Analysis of the clinical interviews revealed that students' ideas about the nature of science ranged from a notion that doing science means discovering facts and making inventions to an understanding that doing science means constructing explanations for natural phenomena. Responses were coded into three general levels of understanding, reflecting the degree to which students differentiate ideas, experiments, and results from one another, and the degree to which they understand and articulate the relationships among these elements. In Level 1, students make no clear distinction between ideas and activities, especially experiments. A scientist "tries it to see if it works." The nature of "it" remains ambiguous; "it" could be an idea, a thing, an invention, or an experiment. The motivation for an activity is the achievement of the activity itself, rather than the construction of ideas. In Level 2, students make a clear distinction between ideas and experiments. The motivation for an activity is verification or exploration of an idea; more specifically, the purpose of an experiment is to test an idea to see if it is right. There is an understanding that the results of an experiment may lead to the abandonment or revision of an idea, but there is still no appreciation that the revised idea must account for all the data, both new and old. In Level 3, as in Level 2, students make a clear distinction between ideas and experiments and understand the motivation for an activity as verification or exploration. Added to this is an appreciation of the relation between the results of an experiment (especially unexpected ones) and the idea being tested. An idea is evaluated in terms of the results of a test and may be changed or developed in accordance with all available data.

The clinical interview results were much more dramatic than the written test results. Before instruction, students either failed to understand the interview questions or at best demonstrated a Level 1 understanding; the overall mean score across the six subsections of the interview was 1.0. Only four students had overall mean scores over 1.5. After the unit, the understanding of all students interviewed improved, and improvement averaged half a level. The overall mean score increased significantly from 1.0 to 1.55 ($p < .001$, Wilcoxon signed ranks test, 1-tailed). Of added significance, sixteen students achieved overall mean scores of 1.5 or better ($X^2 = 7.84$, $p < .01$), and five scored at Level 2 or better (Fisher Exact Test, $p < .03$), a score which no one achieved prior to instruction.

Again, the use of technology to impart metaconceptual knowledge proved the least successful part of the intervention. Because of the constraints imposed by working in classes of 15 to 20 students, only the teacher was able to use the interactive component of the videodisc during a lesson. The group's observations suggested that such teacher control of the videodisc's use was necessary to insure that students engaged in reflection and discussion. Since the lessons on hypothesis testing and on classification schemes could be imparted in an interesting and equally thorough manner without the videodisc, the group does not consider its use crucial to our unit.

Overall Conclusions from Year 4 Classroom Studies

Students' initial conceptions. According to clinical interviews prior to instruction, the seventh-grade students in this study could be characterized as having a Level 1 understanding of the nature of science and scientific inquiry. In a Level 1 understanding, nature is there for the knowing; such a view might be called a "copy theory" of knowledge: knowledge is a faithful copy of the world that is imparted to the knower through encounters with the world. In this view, scientists can be wrong about an aspect of nature only through oversight, that is, through not having examined that aspect.

This Level 1 epistemology provides a context for interpreting the vast literature on children's dramatic failures both at designing experiments to discover causal mechanisms and at interpreting experimental data (e.g., Inhelder and Piaget, 1958, and Kuhn et al., 1988, for a detailed discussion of this point, see ETC Technical Report TR88-19). One reason for these failures may be children's lack of understanding of the distinction between theory and evidence and between the goal of understanding a phenomenon and the goal of producing a phenomenon. In a Level 1 view, knowledge directly reflects reality, so the problem of examining the fit between the two does not arise.

Changing students' conceptions. By helping students to reflect upon the relationship between ideas and the activities of science, the Nature of Science Unit aims to help them begin to differentiate ideas from the evidence that supports those ideas. Although students initially fail to make this distinction, post-interview results indicate that it is indeed possible to move them beyond their initial understanding. After the unit, many students clearly understood that inquiry is guided by particular ideas and questions, and that experiments are tests of ideas. These Level 2 notions indicate their improved differentiation of ideas and experiments — a differentiation that is crucial to understanding the methods of science and the nature of inquiry.

The role of technology. The goal of the Naure of Science Unit is to teach students about the intellectual nature of the scientific enterprise, that is, about the goal of building a deeper and more comprehensive understanding of the world. Technology sometimes plays a valuable and critical role as a tool in the inquiry process: microscopes, telescopes, computers, and other instruments certainly contribute to the scientific enterprise. The scientific enterprise does not, however, rest on the invention or the use of such technological devices. Inquiry is motivated not by technology but by the limits of knowledge in the face of puzzling phenomena. Based on the group's classroom observations, the capacity of the software and videodisc segments to communicate this motivation was limited. Also, given the age and initial Level 1 understanding of the students, instructional goals required that the teacher mediate between the students and the phenomenon being explored in order to promote reflection on the inquiry process. Neither piece of software, on its own, could do this. Suspecting this would also be true of the videodisc segments, the group structured those lessons so that the teacher directed the disc's use.

Does this mean there is no role for technology in imparting points about the nature of scientific inquiry? Not at all. Whenever technology is well suited to building scientific understanding, it is well suited to making points about the enterprise. For example, the Microcomputer-Based Laboratories (MBL) developed at the Technical Education Research Centers give students immediate, visual information about temperature and sound, affording students greater access to a variety of phenomena. White and Horowitz's (1987) series of computer-based microworlds allows students to induce Newton's laws and includes curricular materials about the nature of physical laws, the criteria for deciding what is a good law, and so on. Similarly, both the Weight/Density Project and the Heat/Temperature Project at ETC use the dynamic representational capabilites of computers to provide interactive models of scientific concepts and phenomena. Points about the nature of models, including discussions of what makes a good model, the revisablity of models, the existence of multiple models, and the ability of models to help represent and develop ideas concerning any given phenoemnon, have been incorporated into these curricula.

Year 5: Current work

This year the group has consolidated its efforts in two further studies which address the question of developmental differences in students' metaconceptual understanding of the nature of theory construction and the nature of scientific models. Each of these studies has entered the data analysis stage; the results reported here are preliminary. In addition to these studies, the group has followed up on an earlier review of textbooks (reported in ETC Progress Report TR86-11) by undertaking a more in-depth assessment.

Study 1: Metaconceptual Understanding of Scientific Inquiry in the Domain of Language

Study 1 compares seventh-grade and eleventh/twelfth-grade students' conceptions of the process of scientific inquiry, that is, of theory construction and evaluation, in the domain of natural language. The goals of the study are to assess students' initial conceptions of scientific inquiry both within and outside a theory-building context, and to determine whether it is possible to change their conceptions using a revised and expanded version of the linguistics lessons used in Year 4/Study 1. While the group found in Year 4/Study 2 that seventh graders' conceptions of inquiry improved significantly following instruction, their level of understanding still fell short of the intended Level 3 goal. The Nature of Science Group is investigating whether this shortfall might be due to age-related differences in how much initial conceptions can be changed. The group chose to focus on language phenomena because previous work has revealed that junior high and high school students have few and fairly uniform ideas about such phenomena (see ETC Technical Report TR85-23). This means that students' knowledge of the domain of inquiry is, in effect, controlled across age, affording the unique opportunity to focus on differences in metaconceptual understanding.

Two types of assessment measures — short-answer written tests and individual clinical interviews — were developed. Unlike the measures used in previous studies, these include a theory building component. The written tests present the problem of a Martian scientist trying to account for English language phenomena such as the formation of regular plurals in speech. The tests are highly structured, engaging students in the process of examining the phenomena (e.g., differentiating speech sounds from the written form of the language), organizing the data (e.g., plural words), and constructing a rule (i.e., a hypothesis) that generalizes across the data. The clinical interviews have three parts. The first part probes students' answers on the written tests, providing a context for assessing their understanding of theory construction and evaluation as they are involved in the processs. The second part explores students' ideas about language more generally. The third part further probes students' understanding of the nature of theory construction and evaluation, but does so in a domain-independent context using selected and modified questions from the Year 4/Study 2 clinical interview.

In addition to devising these measures, the group revised and expanded the linguistics lessons from the Nature of Science Unit into a two-week unit. The unit covers two types of language phenomena: a phonological problem of voicing assimilation, i.e., regular plural formation, and two syntactic problems of contraction, e.g., *want to --> wanna*. Both types of phenomena require students to develop an understanding of how to build and evaluate explanations using particular linguistic constructs.

The linguistics unit was taught in three mixed ability seventh-grade classes (n= 32) and two mixed ability, eleventh/twelfth-grade classes (n = 29; hereafter referred to as the eleventh grade). All classes were taught by the same instructor, a group member. Before and after instruction, all students received both types of assessment measures.

Preliminary results. Part of the attempt to assess students' conceptions of theory construction and evaluation is to determine what students conceive an adequate explanation to be. To this end, the group has done a preliminary analysis of the written measures, examining the kinds of hypotheses students construct along two dimensions: the degree to which a rule is "controlled", and the degree to which it is based on sound or spelling. A rule is controlled when there are conditions on the output. For example, a sound-based plural rule of the form, "Add the s sound or the z sound," has no conditions specifying the output, and thus, is uncontrolled. This contrasts with a rule of the form, "Add an s to everything except the words ending with x, ch, sh, ss; add an es to these," which is a fully controlled, spelling-based rule.

Since the coding scheme is in the trial stages, the raw results are presented with no analysis of statistical significance. (Note that the percentages given below do not add to 100 because some students gave no rule.)

The two groups were comparable in their formulation of rules on the pretest: 47 percent of the seventh graders and 45 percent of the eleventh graders constructed partially or fully controlled rules. Both groups improved on the posttest, although the older students showed greater improvement: 69 percent of the seventh graders had a partially or fully controlled rule in contrast to 79 percent of the eleventh graders. If only fully controlled rules are considered, the seventh graders were again comparable to the eleventh graders: 56 percent had fully controlled rules, compared to 52 percent of the eleventh graders.

With regard to whether rules were based on sound or spelling, there was a much greater pre/posttest change for the older group. On the pretest, the seventh graders seemed better able to focus on sound when making a generalization across data: 41 percent had a sound-based rule compared to just 10 percent of the eleventh graders, and only 53 percent had a rule based on spelling or a mixture of spelling-and-sound in contrast to 79 percent of the eleventh graders. This is interesting given that the groups were comparable on other pretest tasks in their ability to differentiate sound from spelling (72 percent of the seventh graders and 79 percent of the eleventh graders were able to do so). By the posttest, however, 83 percent of the eleventh graders had a sound-based rule compared to only 59 percent of the seventh graders; 10 percent of the eleventh graders had a mixed rule (none had a spelling-based rule) in contrast to 31 percent of the seventh graders who had a mixed or spelling-based rule. This may be due to the fact that following instruction many more of the eleventh graders were able to differentiate sound from spelling (97 percent, compared to 78 percent of the seventh graders).

These results indicate that the two age groups are similar in their formulation of rules, although the high school students may have benefitted more from the linguistics lessons. The group is now analyzing the clinical interviews to see whether they will substantiate this finding.

Study 2: Metaconceptual understanding of the nature of models and their use in science

For years, models of natural phenomena and theoretical entities have been widely used as instructional tools for science education. For example, numerous models have been devised to depict the structure of DNA, the relationship of force and motion, and chemical interaction. More recently, with the advent of microcomputers, researchers have begun to explore the pedagogical potential of dynamic microcomputer-based models and simulations. Several groups are paying particular attention to the design and application of models which explicitly represent scientific concepts and their relationships. For example, White & Horwitz (of Bolt Beranek and Newman in Cambridge, MA) have devised an innovative series of microworlds that help sixth-grade students understand the concepts and principles of simple Newtonian mechanics (White & Horwitz, 1987). In addition, the Weight and Density and Heat and Temperature Groups at the Educational Technology Center have found similar computer-based simulations and models to be enormously helpful.

Missing from the science education literature, however, is research on students' understanding of the nature and role of models. Anecdotal reports have suggested that students may interpret models too literally, leading to misassimilation of models they are taught (Deborah Smith, 1984). To address this problem C.Smith et al. (1987) and Wiser (1988) include metaconceptual discussion about the nature of models in their curricula which use computer-based models. Specific studies are needed, however, to determine whether students have <u>systematic</u> conceptions about models (conceptions that are organized as part of an intuitive theory), whether their conceptions about models change with age, and whether the nature of ir conceptions has an impact on how they learn from curricula that rely on models.

The present study was designed to assess students' metaconceptual understanding of the nature and purpose of models and their use in science. Because there was no previous work directly on this topic, the study was essentially exploratory in nature. One of its primary purposes was to develop and validate a scoring scheme describing different levels of student understanding of models.

Recent work by Carey et al. (1988) has investigated seventh-grade students' conceptions of the nature of knowledge acquisition in science. Their clinical interviews with students revealed that students did not share the sophisticated, constructivist epistemology embodied in contemporary philosophy of science. Rather, students seem to hold a naive copy theory of knowle lge acquisition: knowledge is a faithful copy of the world, acquired by passively observing nature, rather than a way of construing the world, actively developed through a process of constructing explanations (i.e.., theories) of phenomenon in nature. This work is relevant because if students have an alternative way of thinking about knowledge acquisition in science, it follows they should have alternative ways of thinking about the nature and purpose of models in science.

The group developed, piloted, and revised a clinical interview to elicit students' initial understanding of models. In this interview, students were asked such questions as: "What comes to mind when you hear the word 'model'?" "What are models for?": "What do yo' ' ave to think about when making a model?" "How do scientists use models?" and "Would a scientist ever change a model?" The interviewers let students give spontaneous answers to these questions and then probed their answers further with follow-up questions such as, "Could you give an example?" or "How would that happen?" In addition, the interviewers presented a number of physical items such as a toy airplane, a subway map, and a picture of a house, and asked students to explain why they thought these could or could not be called models.

Two populations of students participated in this study: 33 seventh graders (sampled across the full range of ability levels in the school) and 22 eleventh graders (in honors science classes). Both groups were from middle class suburbs of Boston. These students were given the clinical interview both before and after they were taught about weight and density (7th grade) and heat and temperature (11th grade).

From a detailed analysis of students comments during the clinical interviews, two coding schemes were developed. ' group identified three general levels in students' thinking about models, which are consistent with the three general levels in thinking about the nature of science described by Carey. Very briefly, these three general levels differ in how the student talks about the relationship of models to reality and the role of ideas in models. In Level 1 understanding, models are thought of either as toys or as simple copies of reali' Models are thought to be useful because they can provide copies of actual objects or actions. If students acknowledg- that aspects or parts of objects can be left out of a model, they express no reason for doing so except that one might want or need to. In Level 2 understanding, the student realizes that a specific, explicit purpose mediates the way the model is constructed. Thus, the modeler's ideas begin to play a role, and the student is aware that the modeler makes conscious choices about how to achieve the purpose. The model no longer must correspond exactly with the real world object being modeled. Real world objects or actions can be changed or repackaged in some limited ways (e.g., through highlighting, simplifying, showing specific aspects, adding clarifying symbols, or creating different versions). However, the main focus is still on the model and the reality being modeled, not the ideas portrayed. Further, tests of the model are thought of as tests not of underlying ideas but of the workability of the model itself. Level 3 understanding is characterized by three important factors. First, the model is constructed to develop and test ideas rather than to serve as a copy of reality. Second, the modeler takes an active role in constructing the model, using symbols freely and evaluating which of several designs could be used to serve the model's purpose. Third, models can be manipulated and subjected to tests in the service of informing ideas. Thus, they may provide information and evidence and play an important role in a dynamic and often cyclic process characterized by observing, thinking, trying, reflecting, and revising.

This general coding scheme is being tested by scoring children's ideas on six separate dimensions. These six dimensions concern the role of ideas, symbols, the modeler, communicative purpose, testing, and multiplicity in model building. Correlational data will provide information about the coherence of the levels across the six dimensions. From this analysis, the group will develop a detailed description of seventh and eleventh grade students' conceptions prior to and after participating in the Heat/Temperature and Weight/Density units and will draw implications for present science instruction.

Textbook review: Analysis of the treatment of the nature of scientific inquiry and knowledge

In Year 3, the group assessed the treatment of the nature of science in 23 junior high school science textbooks and in widely used tests; that work was reported in a progress report, *What Junior High School Students Do, Can, and Should Know About the Nature of Science* (#86-11). During the past half year, the group proceeded with a more in-depth analysis that focuses on the nation's most widely used junior high school science textbooks (as identified in Iris R. Weiss' *Report of the 1985-86 National Survey of Science and Mathematics Education*). This analysis assesses what these textbooks contribute to a constructivist understanding of science.

Using a coding scheme based largely on the one used for the clinical interviews in the Year 4 classroom study, the group did a preliminary analysis of the chapters that deal explicitly with the scientific method and the nature of science. They found, however, that because the coding scheme was not based on the texts themselves, much information about the actual content of the textbooks was lost. In order to retain as much information as possible, they identified the issues addressed by the coding scheme and developed a set of questions to assess the textbooks' treatment of these issues: (1) Do the texts characterize the body of scientific knowledge as cumulative and evolutionary? (2) Do the texts discuss the ways scientific questions are provoked or the reasons why a particular question might be worth investigating? (3) Do the texts discuss the active role of the scientist's mind in the construction of scientific knowledge? (4) Do the texts discuss the motivation for scientists' data-gathering activities (such as observation, experimentation, measurement) and the role of these activities in the development and testing of ideas? (5) Do the texts discuss the effects of data on theory and theory on data? (6) Do the texts present scientific ideas as constructed and falsifiable entities?

Based on the answers to these questions, and on an analysis of the view of science implicit in chapters on evolutionary and atomic theory, the group plans to assess whether the textbooks included in the review contribute to students' misconceptions about the nature of scientific knowledge or help move them to a better understanding. Findings thus far indicate the former.

Future Directions

Science learning, at any age, involves knowledge restructuring and conceptual change; these do not come easily. The Nature of Science Group would like to explore three aspects of how this process occurs and what can facilitate it. First, they would like to test the contention that understanding the process of developing scientific knowledge and understanding the constructed nature of this knowledge will help students interpret evidence that might lead them to restructure their own knowledge. Second, they would like to investigate how students' metaconceptual understanding of models and the use of models in science might help them to learn scientific content, especially when they recognize the power of models to effect their own conceptual understanding of natural phenomena. Third, the group would like to examine the question of transfer: does learning about the nature of scientific inquiry and knowledge in one domain generalize to other domains of science? If such learning involves real changes in students' metaconceptual understanding of science, then such transfer seems likely to occur. Research on these questions would contribute to the development of curricula that will promote conceptual change and enable students to develop real and deep understandings of the domains of science.

RESEARCH IN MATHEMATICS EDUCATION

OVERVIEW

ETC's mathematics education projects have all exploited the computer's ability to display representations of mathematical ideas and to allow students to see and manipulate those representations quickly without tedious computation and hand drawing of figures and graphs. Beginning with work in multiplicative structures in the middle elementary through junior high school years and continuing on to high school algebra and geometry, these projects address much of the core mathematics curriculum currently used in schools.

The Word Problems Project has developed a series of software environments that enable students to explore the mathematical ideas at the heart of much of their difficulty with word problems: multiplication, division, rate, ratio, and proportional reasoning. The software allows students to begin with an easily grasped pictorial representation in which they solve problems through the fundamental acts of matching, grouping, and counting. Later, work at this level is linked systematically to more abstract and mathematically more powerful representations — tables of numerical data, coordinate graphs, and algebraic expressions.

The Geometry Project explores the potential of software entitled the *Geometric Supposer* to reintroduce an empirical component into the geometry curriculum which is traditionally dominated by an emphasis on deductive reasoning. The *Supposer* allows students to make quick accurate geometric constructions and measurements and to repeat those constructions and measurements on any other shape of the same type (triangle, rectangle, or circle). Thus able to generate geometric data, students learn to look for patterns and relationships, to search for counterexamples, and ultimately to use formal proof as a means of confirming their conjectures.

The Algebra Project investigates students' interpretation of coordinate graphs within the context of computerized graphing software. Through clinical interviews the group has identified several metaphors that students use to interpret graphs and has analyzed how these metaphors — mostly based on everyday viewing habits in other contexts — affect students' ability to understand the relationship between graphs and algebraic expressions. Their work has implications for curriculum and software developers as well as for classroom teachers who use computer graphing software.

GEOMETRY

Daniel Chazan, Education Development Center, Project Leader
Ruth Byron, Bedford High School, Bedford, Massachusetts
Richard Houde, Weston High School, Weston, Massachusetts
Gary Simon, Cambridge Rindge and Latin School, Cambridge, Massachusetts
Michal Yerushalmy, University of Haifa, Israel
Philip P. Zodhiates, Education Development Center

The work of the ETC Geometry Project, which began in Year 3 of the Center's existence, has focused on a software series called the *Geometric Supposers*. Created by ETC Co-Director Judah L. Schwartz and Michal Yerushalmy of the University of Haifa in conjunction with Education Development Center (EDC), and published by Sunburst Communications, Inc., this software addresses difficulties with traditional approaches to teaching geometry. The project was based on and benefited from the pioneering work of Yerushalmy and Weston High School mathematics teacher Richard Houde, who outlined an approach to integrating this software series into high school geometry teaching.

The traditional geometry curriculum, touted as a way to teach students to think "logically," relies heavily on deductive thinking and the memorization of postulates and proofs. In this traditional — and often criticized — approach, students manipulate laws and formal representations of geometry without being able to invent laws and test the properties of geometric shapes on their own — that is, without having an empirical component to their learning.

Based in part on Pierre van Hiele and Dina van Hiele-Geldof's theory of levels of mental development in geometry, opponents of the traditional approach claim that many high school students are not ready to operate on a formal, deductive level (Hoffer, 1981) and that geometry, when taught deductively, is a difficult subject for these students. They suggest that because of the abstract nature of geometrical proof, many students end high school mathematics studies after a negative experience with geometry (see Carpenter et al., 1983, p. 654, for course completion data). During the 1970s and '80s mathematics educators and educational researchers have proposed to improve this situation by removing geometry from the curriculum (e.g., Fehr, 1972; Fey, 1984); integrating geometry with other mathematical topics (e.g., Craine, 1985); and reducing the emphasis on deduction (e.g., College Entrance Examination Board, 1985; Campbell and Fey, 1988).

At the same time, many mathematics education researchers and college mathematics teachers decry the state of incoming college students' understanding of the role of proof in mathematics (Usiskin, 1980; Hoffer, 1981; Schoenfeld, 1986). Typically, students have learned to produce mathematical proofs in the context of high school geometry, but even in geometry they appear not to understand the power of a proof (Schoenfeld, 1986).

The *Geometric Supposers* enable users to draw geometric shapes and elements, to make measurements on those constructions, and, most important, to repeat those constructions and measurements on random shapes or on shapes of their own creation. By enabling students to make quick, accurate geometric constructions the software allows students to make and test their own conjectures. Integrating this empirical approach into the traditional curriculum of deductive reasoning and two-column proofs can help students learn about geometry and proof more successfully.

Year 3 Exploratory Study

During its first year, the ETC Geometry Group conducted an exploratory study in three high school geometry classrooms in three different Boston-area communities. This work is summarized here; for a more detailed account, see ETC Technical Report 88–6, *Guided inquiry and technology: A year-long study of children and teachers using the* Geometric Supposers.

The exploratory study proceeded on three levels simultaneously. First, the group clarified Yerushalmy and Houde's approach to teaching high school geometry through the integration of empirical and deductive work and implemented similar approaches in the three classrooms. Student materials created by Yerushalmy and Houde were expanded and modified for these new settings. A researcher visited the classrooms regularly to observe the classes and support the teachers. In addition, the group held regular meetings with the teachers.

Second, the group studied the effects of this approach on students' learning of geometry, focusing mainly on how students make generalizations from particular examples when geometry is taught in this way and on how they formalize their hypotheses and generalizations when they have empirical experiences. Sources of data included pre/posttests on generalization; a year-end test on argument and proof; biweekly classroom observations and notes; and students' written work.

Third, the group explored how the roles of and relationships among students, curriculum and teacher are affected by the new technology (software as well as hardware) in the classroom. Sources of data included minutes of monthly meetings with teachers as well as interviews with teachers and with a sample of students.

Results

Students in the Year 3 Exploratory Study found making conjectures more difficult than the group had anticipated. These students, in contrast to those previously studied by Yerushalmy (1986), had trouble identifying patterns in their data and stating those patterns in general terms. This difficulty led the group to refine the pedagogical approach and identify strategies to foster and facilitate the making of conjectures. By the end of the year, students in the three classrooms were able to make generalizations, even when viewing diagrams. They no longer approached diagrams as static objects or entities; rather, they were willing and able to think about a figure in dynamic terms and to visualize what it meant to move a line or change the characterisitics of a triangle without actually carrying out the construction. When presented with an unfamiliar geometric statement, they were able to consider it and generalize from it. In contrast to a comparison group of students at the same schools in classes at the same level who did not use the *Supposers*, these students were more likely to produce a higher level generalization.

Finally, contrary to the expectations of some mathematics educators, students in the three classes learned to write formal arguments. A three-problem argument/proof test was administered at the end of the year. On two of the problems, students in the *Supposer*-using group were as likely as their counterparts in the non-*Supposer*-using classes to write formal proofs, while on the third problem the *Supposer*-using students were five times more likely to write formal proofs.

Finally, the Year 3 Exploratory Study clarified some of the skills teachers need to structure productive student inquiry and investigation, including the ability to: (1) design problems and problem-solving experiences to teach specific content and inductive skills; (2) know how and when to provide structure and assistance without dampening student initiative; (3) understand and communicate their own problem-solving strategies as models for students to emulate; (4) cope with and support inquiry in a class that has branched off in many directions (e.g., provide guidance and feedback); (5) transform individual student inquiry and findings into a learning experience for the entire class (e.g., facilitate participation, listening, and learning in a math class discussion); and (6) integrate inquiry learning in the laboratory with class material presented in a traditional manner.

Year 4: Inquiry into Student Learning

At the end of Year 3, the group's research pursued two lines of inquiry: the study of how students learn geometry through constructions and conjectures and the study of the complexities of implementing an open-ended inquiry approach in regular classrooms and schools. Plans for Year 4's research were devised so that the inquiry into implementation issues could take place in ETC laboratory sites, including an examination of the personal, professional, epistomological, and managerial issues of lab site teachers as they integrated a powerful but demanding type of software and approach to teaching into twelve geometry classes in four local communities. Members of the Geometry Research Group supported the implementation of the *Supposers* in these classrooms and attended and helped run the monthly meetings of the seven geometry teachers involved in the Laboratory Sites Project. For detailed accounts of this research, see ETC Technical Report 88–1, *Teachers' thinking about students' thinking about geometry: The effects of new teaching tools*, and ETC Technical Report TR88–3, *Guided inquiry with computers in classrooms: Collaborative research goes to school*).

The Year 4 inquiry into student learning focused on two issues that had arisen in the previous year. First, the Year 3 investigation of students' formalization of their conjectures revealed some students to hold the misconception that statements can be proven (without exception) by verifying their truth for some small number of examples. Second, as teachers implemented the guided inquiry approach, they found similarity to be the most difficult topic to teach. Year 4 work therefore consisted of two short-term teaching experiments, the first a detailed examination of students' reasoning about a unit that juxtaposed constructions and deductions in an effort to reduce their confusions about the relationship between supporting evidence and deductive proof, and the second a unit to help students master the vexing topics of ratio and similarity in geometry.

For the first experiment, the group designed and tested a unit on proof and devised a questionnaire to elicit students' views of proof. Teachers were provided with particular problems to use in the computer lab and with loose scripts indicating the goal of each problem. The proof unit was taught in four classes, two that used the *Geometric Supposers* and two that did not. The questionnaire was distributed to all four classes at the beginning and again at the end of the unit to identify students who had held this misconception. These students were then interviewed.

The second experiment assessed the effectiveness of a unit designed to help students with the topics of ratio and similarity. This unit addressed three areas of student difficulty identified in prior research: (1) understanding of ratio and proportion as an aspect of similarity; (2) understanding dimensional growth relationships, or the relation of change in the lengths of sides of similar figures to the change in the measures of other dimensions; and (3) proportions (among the lenghths of sides) in right triangles with an altitude from the right angle vertex. A pre/posttest, adapted in part from the Chelsea Math Test series, was administered to six classes, four who used the *Geometric Supposers* and two matched in ability and curriculum who did not use the *Supposers*. The unit consisted of eight tasks designed for use with the *Supposers* in a computer lab during class time. In the *Supposer*-using classes, teachers added these tasks to their existing similarity unit. The group developed a four-part clinical interview to probe students' notions of similarity and used this interview with students selected from all six classes to represent a range of abilities.

As an adjunct to these teaching experiments, the group devised an additional questionnaire, adapted in part from questionnaires developed by mathematics education researcher Elizabeth Fenema, on attitudes toward mathematics and mathematics learning. This instrument was administered to students in the six classes.

Results

At the end of the proof unit, most students in classes using the *Supposer* no longer believed that verification by measurement of examples is proof; experience with counterexamples had convinced them that measurement of examples does not show that a counterexample does not exist. Many students in the classes not using the *Supposer* continued to hold this misconception, and some students held a second misconception. They seemed to believe that proofs prove statements only for the particular diagram that accompanies the proof. According to this view, a deductive proof is no more than a verification of a statement for a single instance (for a case study of one such student, see Chazan, in press). A new set of exercises was needed to address this misconception and further research was indicated. Finally, students' responses to the questionnaire disclosed that the questionnaire itself needed revision.

The three difficulties identified in previous research about students' understanding of ratio and proportion were also displayed by the students in this study. Students often exhibit the first difficulty, understanding of ratio and proportion as aspects of similarity, when given tasks that ask them, for example, to take one triangle and make a similar one by extending two sides of the original. The common pattern is to use an incorrect additive strategy, adding an equal length to each side of the figure, rather than a multiplicative strategy which would preserve the figure's proportions. In this study, researchers found that both direct and indirect attention to this incorrect strategy helped some students change. The research also indicated that some students' use of additive ratio strategies in geometrical contexts may have a geometric basis as well as a numerical one. Because of students' difficulty with the definition of "distance," configurations involving parallelism seemed particularly likely to elicit this misunderstanding. The additive misconception was much more prevalent on such production tasks than on numerical proportion problems.

To address the second difficulty, understanding similarity in dimensional growth relationships, teachers in this study used two strategies: providing students with a formula and having students generate the formula by doing a computer task. Researchers found that by the end of the unit, most students recognized the growth relationships that hold for solids, but many could not apply their knowledge to explain figures. Most did not understand the relationship of sides, areas, and volumes to represent one underlying relationship. In some cases, students appeared unable to reorganize their perception of a whole figure to highlight a particular dimension.

This study tested two hypotheses about the source of the third difficulty, understanding correspondences in right triangle similarity: (a) that students have trouble recognizing the similarity of triangles that must be flipped to be superimposed with their corresponding sides aligned and (b) that they find similarity relationships in right triangles difficult because in the typical configuration the altitude functions as a segment in three triangles and as a side in two. Results on this point were inconclusive; data supported neither hypothesis strongly.

A set of activities designed to address these misconceptions was outlined in the appendices of ETC Technical Report TR88–15, *Similarity: Exploring the understanding of a geometric concept*. The insights into students' understanding of similarity, gained from classroom observations during this study, suggest that when microcomputer tools are used in a guided exploration approach, the computer lab sessions can be an important and valuable tool for research on students' understanding.

Year 5

In Year 5 the Geometry Group continued one aspect of its empirical studies of students learning geometry and focused the rest of its efforts on synthesizing and disseminating the results of its research on the *Supposer* innovation. The division of labor between the Laboratory Sites Project and the Geometry Project continued and, as in Year 4, Geometry Group members attended the monthly meetings of the lab site teachers using the *Supposer.* Descriptions of research on the implementation and spread of the geometry innovation are described in the Laboratory Sites Project section of this report.

Dissemination

During this year members of the group drafted a book about teaching high school geometry through conjecturing. This book was accepted for publication in the *How To...* series of the National Council of Teachers of Mathematics.

Members of the group also produced a paper about posing problems for student inquiry in the classroom. The paper presents six considerations for creating such problems and provides examples from the materials that have evolved from the group's cumulative experience. The paper also offers observations about strategies that teachers use to address the six considerations and, based on a careful examination of students' papers, recommends ways to create inquiry problems for use with the *Supposers* and draws general lessons for other inquiry environments in classrooms (see ETC Technical Report TR88–21, *Posing problems: One aspect of bringing inquiry into classrooms*).

Finally, members of the group acted this year as support staff for the creation and development of an electronic network of *Supposer* users through the Ford Foundation's Urban Mathematics Collaboratives (UMC). Using this network, UMC teachers throughout the country discussed their use of the *Geometric Supposers*. Group members were available to answer questions and to ask questions to stimulate discussion.

Preliminary Results of Year 5 Research

At the end of the Year 5 unit on proof, even students whose initial answers to the questionnaire indicated that they thought measuring examples could prove a statement, responded that measuring a large numb of examples does not prove a counterexample does not exist. They understood the limitations of measurement of examples.

Students who believed that a proof proves a statement only for a single diagram had many different reasons for holding this view. Some had not distinguished deductive proof from measurement of examples. Their experiences with counterexamples shook their belief in general proof. Others had difficulty understanding that the "givens" in a proof indicate a class of geometrical objects. When presented with a proof, complete with "givens" and a diagram, they were unable to distinguish between the parts of the diagram that could not be changed and those that could be changed. Still other students were confused by the wording of proofs. In their reading of proofs, they ignored language signifying plurals and assumed the argument was being made in the singular. When the proof was read with an interpolated emphasis on the general nature of its steps, these students expressed surprise and explained they had not believed that was the intent of the proof.

Future Research

The Geometry Project has made progress in four directions: clarifying an inquiry approach for using the *Geometric Supposers* in classrooms; documenting the success of this approach in producing positive student learning outcomes; researching questions of students' understanding of geometry; and disseminating the inquiry approach. Future efforts should be made in each of these directions.

Although the project has made great strides in specifying its inquiry approach, much remains to clarify. Probably the most urgent clarification is of the inquiry skills students need to develop in their lab work. When these are clarified, materials can be written to help teachers understand how to help students learn these inquiry skills. This development should strengthen the effects of inquiry approaches using the *Supposers*.

The project has provided evidence for the success of the *Supposer* innovation by demonstrating improved student performance (in tasks of generalization, formal argument, and similarity), identifying opportunities for teaching metaconceptual points about proof, and affecting students' attitudes toward mathematics. This work should be replicated. Now that teachers have been using this approach for a few years and the novelty has worn off, similar positive results would be impressive indeed.

Regarding dissemination, one of the most pressing needs is for training of teacher educators who can do workshops for teachers interested in guided inquiry approaches to teaching geometry with the *Supposers*.

Finally, on the basis of experience with the *Supposer*, extending the inductive, empirical, conjecturing approach to other areas of mathematics education would seem valuable.

WORD PROBLEMS

James J. Kaput, ETC/Southeastern Massachusetts University, Project Leader
Kathy Hollowell, Newton North High School, Newton, Massachusetts
Joel Lubin, Weston Middle School, Weston, Massachusetts
Clifton Luke, ETC
Laurie Pattison-Gordon, ETC
Joel Poholsky, ETC
Yolanda Rodriquez, Martin Luther King School, Cambridge, Massachusetts
Aline Sayer, ETC
Judah L. Schwartz, ETC/Massachusetts Institute of Technology
Jane West, Newton South High School, Newton, Massachusetts

Mary Maxwell West, ETC
Philip Zodhiates, Education Development Center

Five years ago, participating teachers led this project to focus on that b‹ .e of school mathematics, the "word problem." The group's point of view was — and still is — that the key act students must learn is to use mathematical concepts and representation systems to model phenomena in the world. Hence, "word problems" as classroom/textbook rituals were not the instructional or curricular target. Rather, the group was interested in the much more general and useful skill of *using mathematics as a personal resource to make sense of one's world*.

During the first two years of the project the group refined this target of difficulty to mean students' use of that area of mathematical ideas and notations related to multiplication, division, rate, ratio, and proportion — the area that has come to be known as the conceptual field of "multiplicative structures" (Vergnaud, 1983). This refinement resulted from surveys of student performance on various classes of problems to determine which types were most difficult (Schwartz, 1984). The target was further refined by analyzing the structure of the mathematical ideas at the core of these difficult problems and the situations to which they apply.

This analysis led to the realization that the key underlying concept was the idea of "intensive quantity," a concept that subsumes rate, ratio, and even the notion of scale change. The idea of intensive quantity was analyzed in terms of the various situations to which it applies as a mathematical model, its relationships with the operations of multiplication and division, and its place in a larger theory of quantity (Schwartz, 1988). In one sense, then, the project can be thought of as extending earlier work in the conceptual field of additive structures (e.g., Carpenter, Moser, & Romberg, 1982) to this more complicated domain that is notorious for learning obstacles and curricular weaknesses (Corbitt, 1981).

Once this focus was sufficiently clarified, the group undertook a review of the curricular and cognitive foundations of the students' difficulties with intensive quantities. A wide ranging review of relevant past work and an analysis of the existing mathematics curriculum led to a critique of the curriculum and an alternative curricular framework for developing the idea of intensive quantity (Kaput, 1985). The current literature on mathematics education reform pinpoints several shortcomings in the existing curriculum on multiplicative structures, e.g., too much emphasis on computation and formulaic approaches to every topic (McKnight, et al, 1987). In its own critique, the group identified several additional serious weaknesses, including a paucity of application models for multiplication, a failure to distinguish systematically the different forms of division, and a general lack of longitudinal coherence. The latter is reflected, for example, in treatments of ratio and proportion apart from their real status as expressions of linear quantitative relationships, and coverage of rates, ratio, scale change, density, etc., as if they were unrelated ideas, when, in fact, they are all examples of intensive quantities.

In surveying the existing curriculum and developing a plan for an alternative approach, the group decided on strategic grounds not to deal with the full rational number curriculum. Instead, it started with discrete intensive quantities, where the arithmetic is simplest and where a reasonable conceptual distance can be maintained between the part-part relationships associated with discrete intensive quantities and the part-whole relationships that are typically the basis of students' experience with fractions (Behr, Lesh, Post, & Silver, 1983).

Review of cognitive research suggested that students are unable to apply the multiplicative structures ideas viably and flexibly because they lack cognitive models of the mathematical operations. For example, students saw multiplication only as repeated addition (Fischbein, et al, 1985; A. Bell, Fischbein, & Greer 1984; Usiskin & M. Bell, 1983). Later the group also found that students did not see a connection between their algorithms for division and the process for finding a missing factor when given the product and the other factor (Kaput, Luke, Pattison-Gordon, & West, 1988).

Having localized and traced the cause of student difficulties with applying the mathematics of multiplicative structures to *the lack of sufficiently rich, flexible, and organized mental models of multiplication, division, and intensive quantity*, the group turned more directly to the design and testing of materials and environments that might support the development of such mental models — or, as the group has come to describe them, "cognitive representations."

One critical step was a design decision to build and test learning environments that embody *multiple, computer-based, and action-linked representations of the target mathematical ideas*. The decision that they should be computer-linked followed from the hypothesis that one might build an enduring, tightly linked web of *cognitive* representations by providing experience with a variety of linked *external* representations. The forms of those representations followed from the group's curricular goal that students should learn the representations that will carry them into the large body of mathematics that lies ahead and from empirical work using paper/pencil activities that helped identify promising concrete starting points for learning the central idea of intensive quantity.

The early versions of these prototype learning environments were attempts simply to show that several representations were actually linked, as reflected in Figure 1, which depicts three representations of the discrete intensive quantity, "2 trees per 3 people": an iconic (upper left), a numerical (upper right), and a coordinate graphical (lower right) representation. Since then, the group has added an algebraic representation using simple equations. As always, the environments presume a context for the ideas involved; in this case, for example, the context might involve planting trees for a picnic park where each group of 2 trees is assumed to shade 3 people.

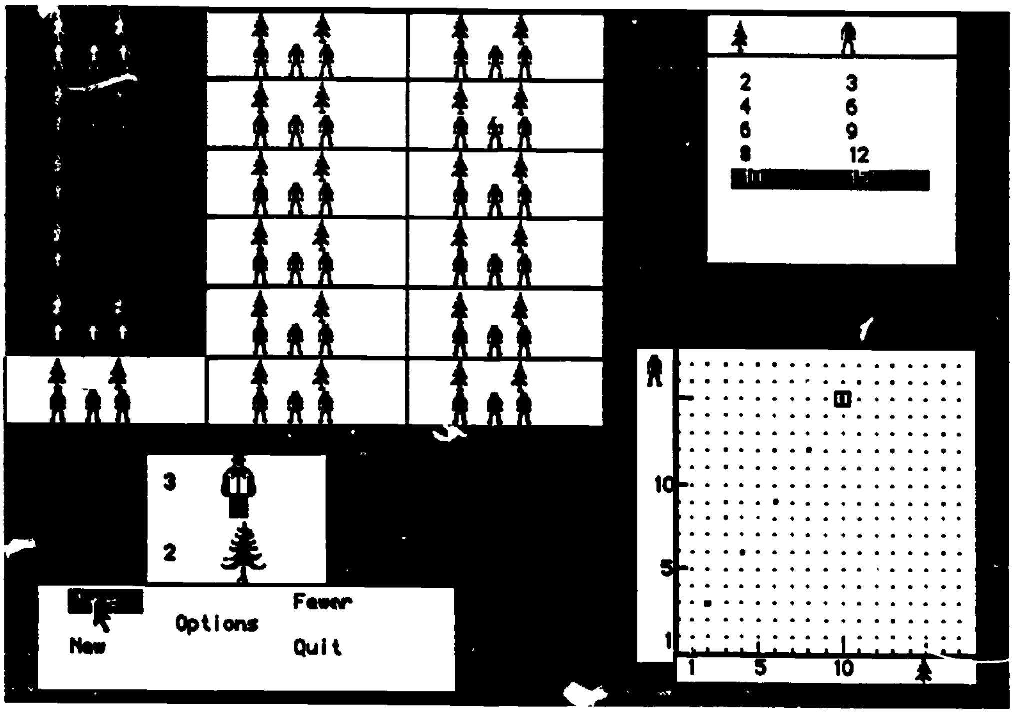


Figure 1

Here, the user's only action is to click on the MORE and FEWER buttons to increment or decrement the numbers of objects highlighted in the iconic representation. This action applies simultaneously to all three representations, although any of them may be turned off as desired. Clinical sessions with approximately three dozen sixth and seventh graders revealed three shortcomings of this use of tne linked representations: first, one does not act on the representations themselves, but rather gives "representation-transcendent" commands that apply to all three representations at once; second, the incrementing or decrementing actions do not adequately support the varieties of strategies that one uses in proportional reasoning; and third, the iconic representation does not adequately exploit the "objectness" of the screen objects available in the kind of bit-mapped computer display that will soon be common in school computers.

These considerations, together with the need to build the cognitive models cited earlier, led to the construction of what the group came to call a "concrete-to-abstract software ramp" (Kaput & Pattison-Gordon, 1987) that responds to these shortcomings. Thus, for example, the group expanded the iconic representation, creating environments in which the user can do the computation required for discrete multiplication, division, and ratio reasoning (reasoning with discrete intensive quantities) by manipulating objects on the screen. This required an examination of the interaction between the manipulable concrete representations of the fundamental acts of grouping and counting that underly discrete multiplication, division, and ratio reasoning and the mental construction of these operations. In addition, these changes led the group to reconsider how these concrete representations could be linked to the more abstract representations used in subsequent mathematics.

The full software ramp is described below in the context of the group's current work. The pedagogic approach embodied in all the learning environments is to put students in situations calling for actions using a particular representation, where *the students* are then responsible for judging the adequacy or appropriateness of those actions. Usually they make such judgements by interpreting consequences of their actions in a representation different from the one in which they initiated the action, where their judgement is facilitated by the explicitness of the representation itself rather than by the computer acting as a kind of omniscient "expert" arbiter of appropriateness. *Thus the computer reports, and the students evaluate,* not the other way around.

Summary of Empirical Work in Years 3 & 4

The clinical testing of various forms of the software environments during the third and fourth years of the project involved approximately 100 children, mainly in grades six through eight. Late in the fourth year, as the group addressed the cognitive foundations of ratio reasoning, third through fifth graders also participated in the research.

During the summers of 1986 and 1987, the group conducted exploratory dual teaching interventions with two small groups, one with entering fifth and sixth grade students and the other with entering sixth through eighth graders. In 1986, the intervention was five sessions in length using an earlier set of computer environments, and in 1987 it was ten sessions, spread across 3 weeks in an urban school setting with primarily academically disadvantaged students using an expanded set of environments. Follow-up clinical interviews of six of the older students were conducted six months later.

Current Perspective

The group's view of the curriculum and the associated application of the technology have dictated from the beginning that these kinds of learning environments need to be used over a period of several years and grade levels. The clinical work confirmed that students need extensive experience with such environments. Thus, the researchers eschew quick-fix or local technological solutions to difficult and longstanding learning problems. They believe that *important, complex conceptual structures take many years to develop and require a global curriculum development strategy informed by [illegible] deep research.* To shortcut either the research or the extended meaning-building process, perhaps in the hope of achieving near-term and easily measured procedural performance, is to invite the sort of long-term disaster that is currently reported in many nations around the world (McKnight, et al, 1987).

The empirical work associated with testing and revising the software ramp, made plain that the *key cognitive research goal is to explicate as well as possible the interactions between reasoning processes involving multiplicative structures and the different external representations that are, or can be made, available for use by students and* *teachers.* A fuller description of the group's theoretical perspective on representation and the associated issue of meaning-building can be found in (Kaput, 1987; in press a, b).

Finally, the overall curricular goal likewise became plain: *to build the foundations for a cognitively richer and more complete multiplicative structures curriculum that begins more concretely than does the current one and ends with more abstract and powerful representations that lead to the important mathematics beyond, but is more efficient in the sense that it builds the required conceptual and computational power at a lower grade level than is now the case.*

Outline of the Software Environments

The group's clinical work led to the organization of the software into the top four environments indicated in Diagram 1, as described in Kaput et al. (1987) and more fully in Kaput and Pattison-Gordon (1987). The fifth, continuous environments, are in early prototype form.

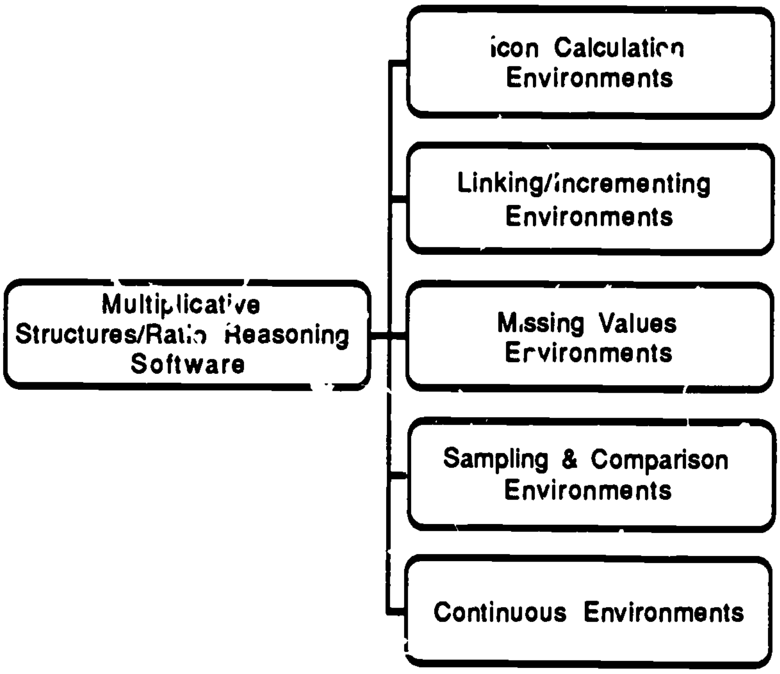


Figure 2

All activity in the environments in Figure 2 centers on problem situations so, in effect, these are modeling environments. In particular, the top four environments support the modeling of multiplication, division, and ratio reasoning situations with discrete quantities. All the programs run on Macintosh computers. The icon-object based calculation environments that students begin with attempt to capitalize on the bit-mapped graphics and the use of the mouse to manipulate screen objects in a way that exploits children's common experiences with objects. The Word Problems Group believes that these experiences with grouping, matching, and counting can form the foundation for arithmetic operations as well as for ratio reasoning with discrete quantities. Later, the group uses the power of the computer to link these concrete representations to more abstract ones.

Each environment begins with students choosing icon(s) to represent the items in the situation being modeled. Presented with a screen filled with icons representing common objects (see Figure 3), students must point to an icon and click the mouse button to make their choice. The following sections describe the environments listed in Figure 2.

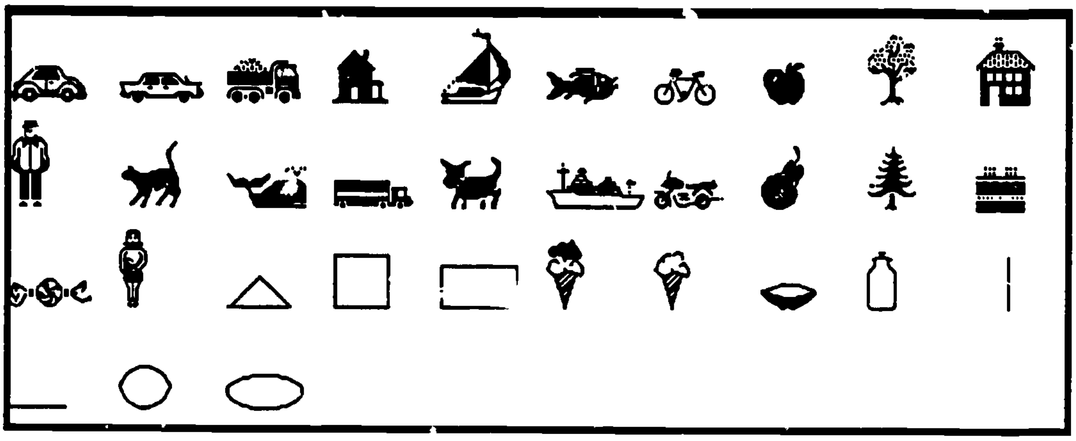


Figure 3

The Concrete End of the Concrete-to-Abstract Software Ramp

The software ramp begins at the most concrete level with the icon calculation environments, of which there are two families, as indicated in Figure 4.

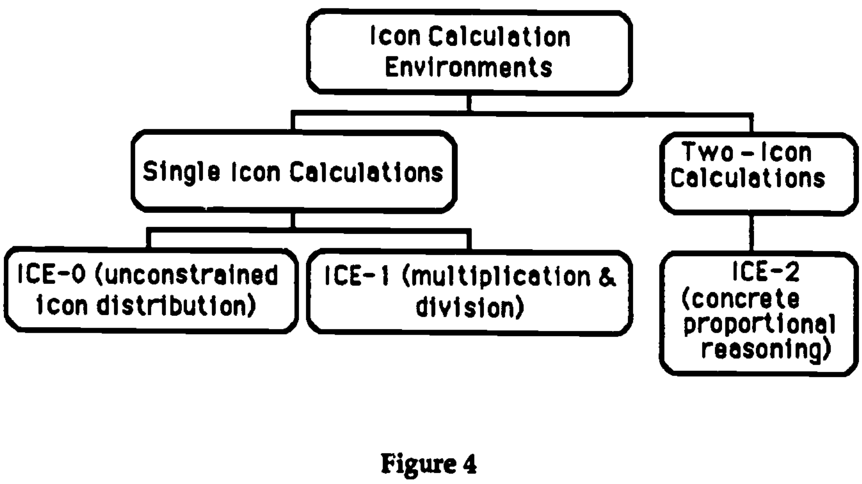


Figure 4

One family, ICE-1 (in the left-middle of the diagram) supports calculations with single icon sets: multiplication and the two forms of division. ICE-0 can be used as an organizer for simple calculations of any kind. It acts simply as a "game board" on which one can take icons from a reservoir and freely distribute them in a rectangular array of cells.

ICE-1 provides concrete, enactive means for solving the equation $E' = E*I$ for any of its quantity-variables when given the other two. Hence, three problem types are possible, one for each possible missing value in the equation, each of which has a distinct set of icon-object manipulations constituting its solution. The letters E and E' denote extensive quantities and the letter I denotes an intensive ("per") quantity. The quantity E' is instantiated as the number of objects, E as the number of boxes, and I as the number of objects per box. Thus, with reference to the data-input window in the lower right corner of Figure 5 below.

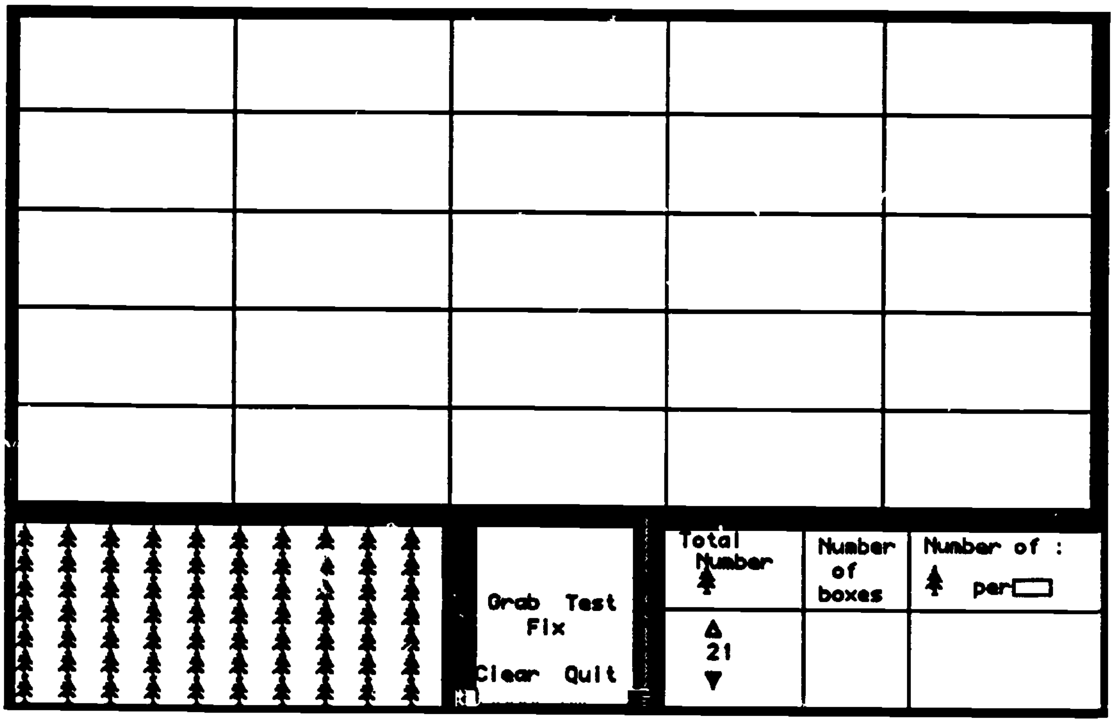


Figure 5

providing the three problem types amounts to providing numbers in two of the three positions of that window and requesting the third. Suppose the problem involves planting trees, for example, and the student has chosen the tree icon in ICE-1. This leads to a screen such as that pictured in Figure 5, when the student enters the total number of trees given in the problem.

More generally, the environment allows the student to model concretely any of these three types of situations which were abstractly represented by the above equation:

(1) providing the number of boxes and the number of icons/box yields a "rate" type of multiplication problem — find E*I: *the total number of icons;*

(2) providing the number of boxes and the total number of icons yields a partitive (fair share) division problem — find E'/E: *the number of icons/box;*

(3) providing the number of icons/box and the total number of icons yields a quotative (or "measurement") division problem - find E'/I: *the total number of boxes.*

A variety of options and scaffolding are available to support grouping, matching, and counting. After the given numbers are entered (by the student) or provided by the computer, the user determines the third by an appropriate grabbing and dragging action, depositing the objects into the rectangular cells. In Figure 6, for example, the user is determining how many apples will be needed altogther if four children are to get three apples apiece. The user is grabbing and dragging three apples at a time into the cells (grouping three at a time is not necessary unless computer help is asked for, in which case the computer constrains the grabbing process so three are grabbed automatically). Here the user is using the respective boxes (cells) to represent the children, so that the semantic relation of "giving" apples is modeled directly by the act of depositing the apple icons in a box.

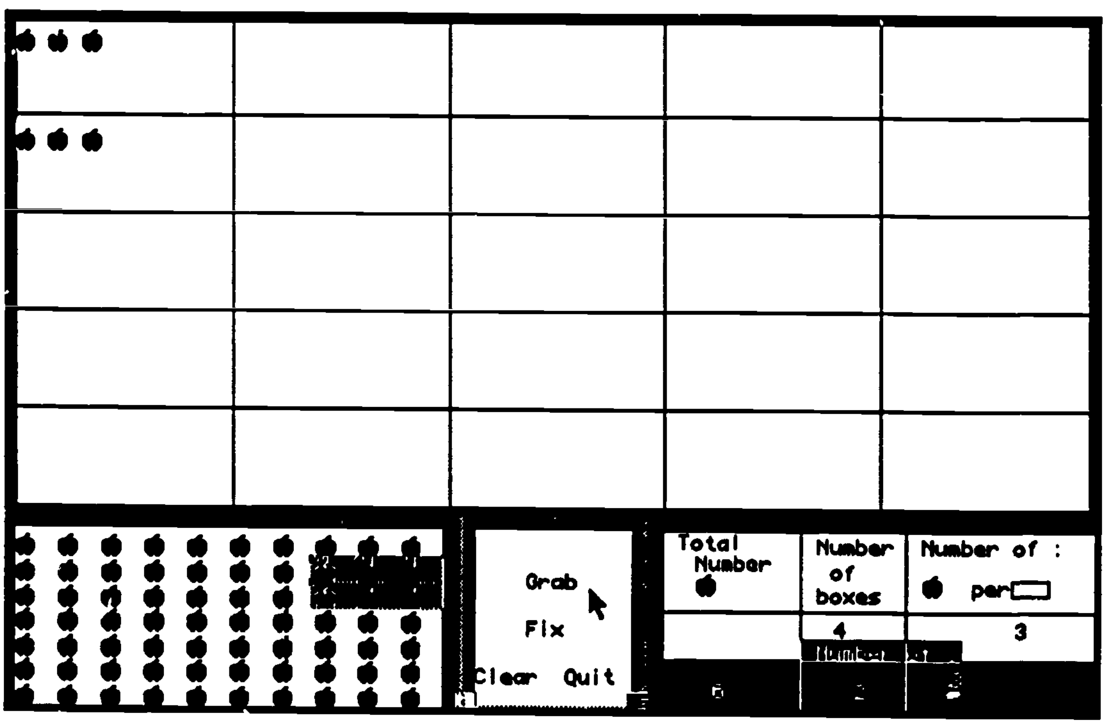


Figure 6

The computer keeps track (in inverse video) of how many objects and boxes have been used, and, if the number of items deposited per box is the same for all boxes, it displays that number as well.

In Figure 7 the problem situation is partitive division — if 20 apples are given equally to 5 children, how many will each child get? Here, the apples are distributed in the "round-robin" one-at-a-time style that is used by most preschool children (Hunting & Sharpley, 1988; Zweng, 1964, 1972). If the problem were its numerical <u>quotative</u> equivalent — if twenty apples are to be distributed so that each child gets five, how many children will get apples? — the more likely distribution pattern would be to grab and distribute five apples at a time (again supportable by a computer scaffolding option that assists with the grabbing process). Thus, the two forms of division, formally identical, have explicitly different concrete enactments in ICE-1.

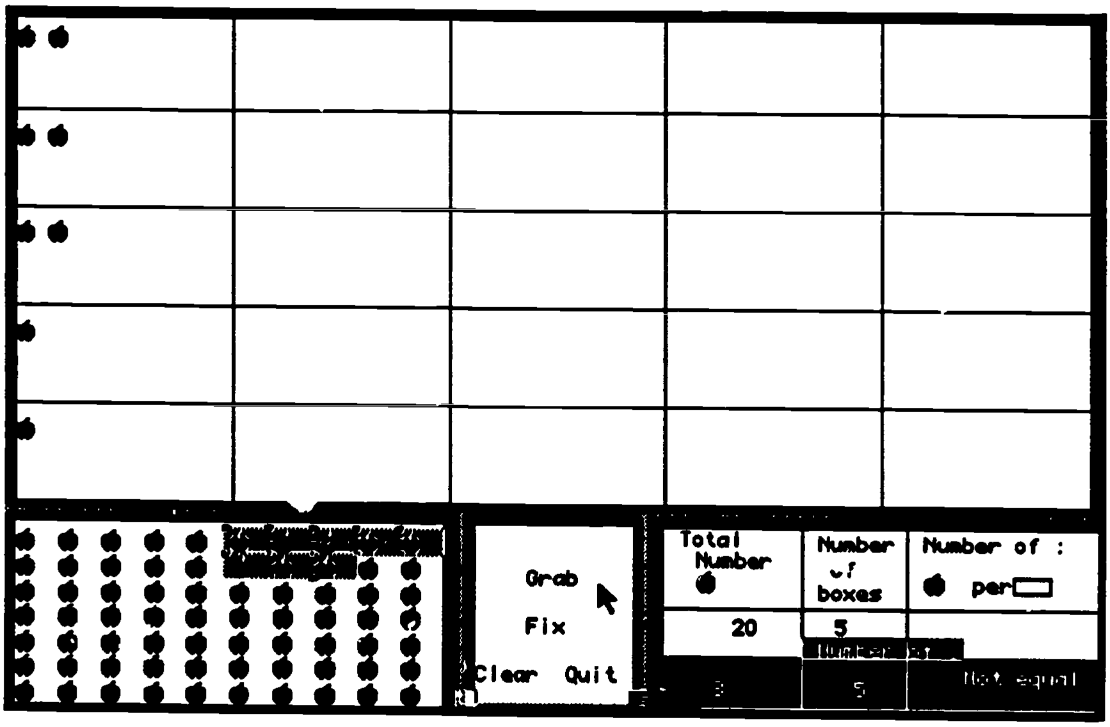


Figure 7

Concrete Ratio Reasoning

The second type of concrete calculation environment, ICE-2 (on the right side of Figure 4) supports calculations coordinating the distribution of <u>two</u> sets of icons, as occurs in whole-number proportion solving. In this context, proportional reasoning — historically assumed to be a difficult reasoning process requiring substantial intellectual development — can be accomplished using only the fundamental cognitive acts of grouping, matching, and counting. More than one icon-distribution strategy can be used to solve a traditional missing value problem, depending in part on the conditions under which the problem is solved. For example, consider the following problem situation:

> *We are planning a park in which we want to plant trees in such a way that each two trees can shade three people. If we plant 14 trees, how many people can be shaded?*

A popular "boxes strategy" requiring little teaching takes the following form: Divide the number of trees (14) by 2 trees/box to get 7 boxes (an E/I, a quotative, division) and then multiply 7 boxes by people/box to get the answer, 21 people. Its "spread out" or unabbreviated concrete embodiment is as follows:

(1) Distribute 14 trees into cells, grouped 2 per cell — the quotative division step.

(2) Match each of the groups of 2 trees with a group of 3 people — the multiplication step.

(3) Count the number of people icons, using either the gray shadows in the people icon reservoir or the people icons in the cells — the counting step.

The layout in Figure 8 is a depiction of Step 2 *in medias res*. Note that the user chose the "computer help" option for the number of trees — only the number of trees needed (14) was available in the reservoir, and all the others were blanked out.

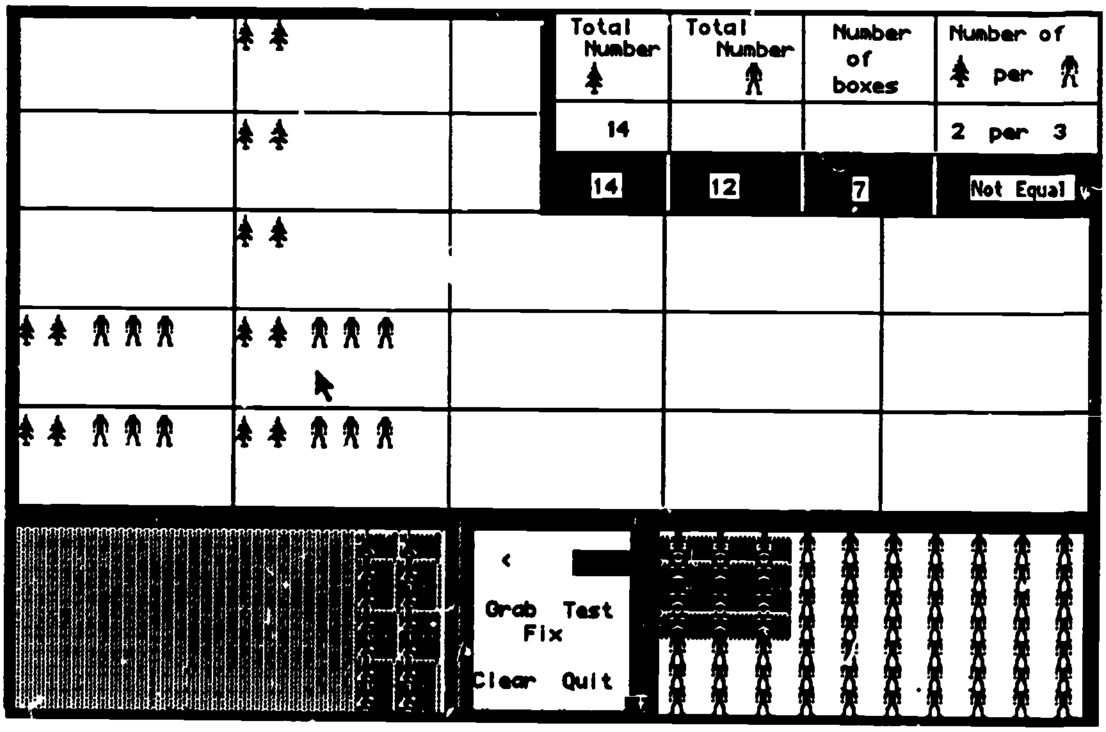


Figure 8

Linking to More Abstract Representations

The process of ramping upward from these concrete reasoning environments to the more powerful mathematical representations such as coordinate graphs and algebraic equations is achieved through the application of a set of Linking/Incrementing Environments, one of which (sans algebra window) is pictured in Figure 8. These environments support simple acts of incrementing and decrementing by clicking on the MORE or FEWER buttons. Here the student can examine at will the linked consequences of these acts in any or all of four representations: Iconic, Numeric (tables of data), Graphic (coordinate graphs), and Algebraic (equations). Note, of course, that the representations are introduced one at a time and are seldom all present simultaneously. One can toggle a representation from active to inactive to entirely blank by clicking anywhere on its right hand boundary. There are also intermediate representations designed explicitly to facilitate the transition from the concrete to the abstract, for example, the transitional coordinate graph that stacks icons along the axes instead of simply labeling them with numbers.

Missing Values Environments

Once new representations are available for proportional reasoning, the student can explore the different forms of that reasoning process across the representations. The primary form of proportional reasoning is embodied in what are typically referred to as "missing value problems." In the Missing Values Environments students can input solutions in any of four representations and check the results achieved in any of the others. This power of a "representational second opinion" is most often exercised when a student uses a more concrete representation (iconic or numeric) to check on computations done relative to a more abstract representation (coordinate graph or algebraic equation) — see Figure 9.

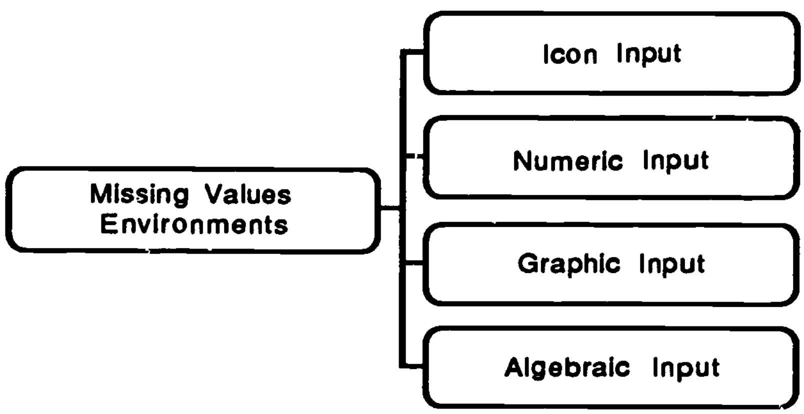


Figure 9

Sampling and Comparison Environments

Another aspect of intensive quantities relates to their use in the describing of an internal feature or attribute of a substance, entity, or situation — for example: density in grams per cubic centemeter, speed of a car on a trip in miles per hour, or number of candies per child. This aspect of the complex idea is addressed in a series of four sampling environments where the matter of homogeneity of samples is also addressed, e.g., is the density constant?

These sampling environments also support the comparison of intensive quantities. For example, if one park's picnic area has 2 trees per 3 benches, and another has 3 trees per 9 benches, which is shadier?

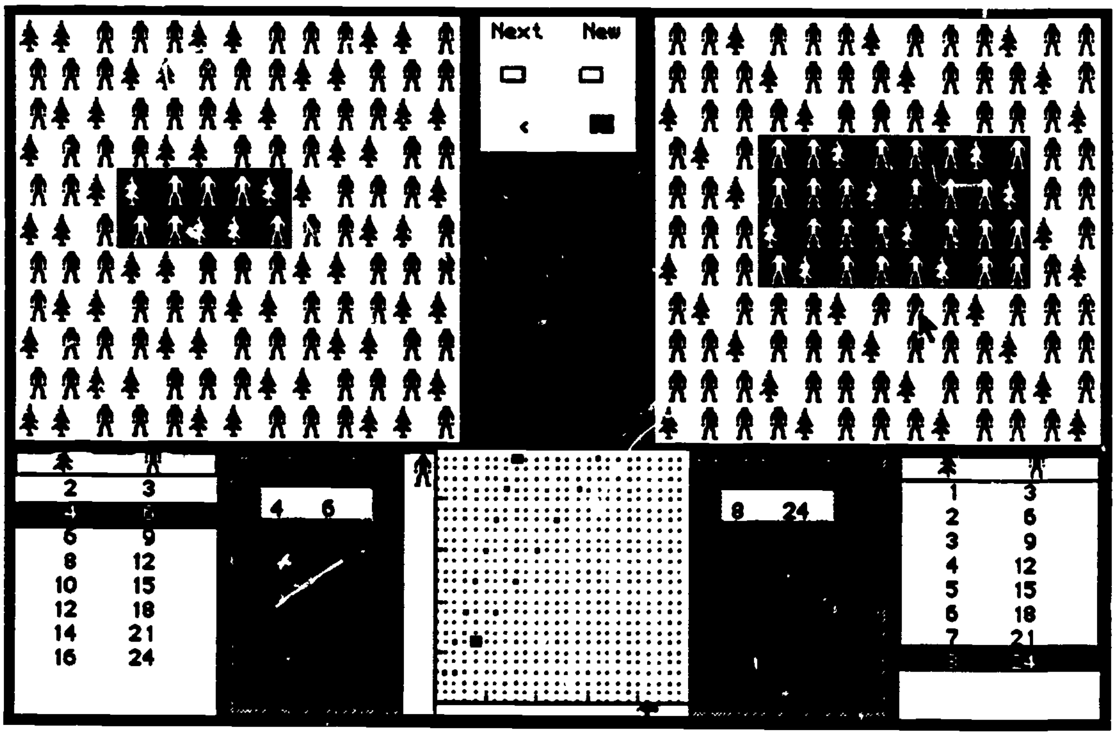


Figure 10

In Figure 10, parallel samples are taken from the two sets of icons. The results of the sampling process are stored in the two-column table and the coordinate graph. Thus, these environments engage yet a third aspect of this web of ideas, that of order (Kaput, in press c; Kaput & Pattison-Gordon, 1987).

Slopes of Lines and Order Comparisons

In dealing with order these environments also engage the grouping of groups, e.g., the groups of "two trees" and "three people" are brought together to form a single entity, the pair of groups. Among the particular representations that support this entity as an argument in ordering and comparing procedures is the coordinate graph, which represents each intensive quantity as the slope of a straight line of points in the plane, that is, as a single attribute (slope) of a single object (the line). Thus, to compare two intensive quantities with respect to size, one need only attend to two items (lines) whose relative size maps onto a directly observable, linearly ordered attribute space - the visible slopes. In contrast, the relative size of the intensive quantities is often deeply implicit in the four numbers involved when the other representations are employed. See Figure 10 above for an illustration of how the role of the external representation is clearly evident in comparison tasks - a good example of how particular features of one external representation support particular reasoning processes whereas the features of others do not.

Future Directions

In order to build the cognitive foundations for further development of a multiplicative structures curriculum and to consider how these topics should be integrated into existing curricula, the group is carrying out in 1988-87 a teaching experiment in a suburban Boston middle school. Four two-week units will be used in four sixth-grade classes and one eighth-grade class; several other classes will use a traditional approach. Written pre/posttests for all students and interviews with a subsample will assess student undestanding of multiplication, division, and ratio concepts and their applications. If successful, this teaching experiment and the project of which it is a part will provide the basis for a substantial restructuring of the core quantitative mathematics curriculum in grades three through seven. For further information on the project, see the several papers and technical reports by project staff that are cited in the References section of this report.

ALGEBRA

E. Paul Goldenberg, Education Development Center, Project Leader
Sharon Booth, ETC
Ruth Byron, Bedford High School, Bedford, Massachusetts
Kathy Hollowell, Newton North High School, Newton, Massachusetts
James J. Kaput, ETC/Southeastern Massachusetts University
Stephen Kellogg, Park School, Brookline, Massachusetts
Marc Konvisser, Worchester Polytechnic Institute
Kit Norris, Fenn School, Concord, Massachusetts
Lianne Ritter, Buckingham, Browne & Nichols School, Arlington, Massachusetts
Richard J. Umiker, St. Marks School, Southborough, Massachusetts
Jane West, Newton South High School, Newton, Massachusetts
Philip Zodhiates, Education Development Center
Wayne Harvey, Education Development Center
Philip G. Lewis, Lincoln-Sudbury Regional High School, Sudbury, Massachusetts

Graphing has traditionally been a paper-and-pencil activity which, because of the time and effort involved, has not constituted a large part of mathematics curricula. This is changing as greater classroom access to computer graphing makes it easier for students and teachers to create and manipulate graphs and to explore the relationship between those graphs and the symbolic representations of the same functions. The growing interest in the curricular use of graphing raises a need for insight into students' approaches to the graphing process. Because generating and exploring graphs will be performed most often in a computer context — and because millions of dollars are being spent to develop graphing software for educational use — educators and software developers must understand how students respond to computer-generated graphs, and we must study the human factors of student interaction with various command interfaces.

In addition to the software design considerations, the heavy use of graphing raises some mathematical issues, particularly in the computer context. For example, issues of *scale*—of paramount importance in understanding both graphs and the concept of *significance* as it is used in mathematics—are typically not noticed and may even be deliberately avoided in paper-and-pencil work. In the computer context, however, scale issues are nearly inescapable.

Ultimately, these developments draw attention to some larger educational questions: Are students really helped by having an interactive laboratory in which to explore linked graphical, symbolic, and tabular representations of functions? That is, is their mathematics really more robust, error-free, or enjoyable? If so, what are the implications for the curriculum? How must it adapt to make the best use of the new mathematical laboratory?

To answer such grand questions, however, researchers must study not a piece of software, but a well thought out and coherent curriculum that makes significant use of a well thought out piece of software. To develop such an intervention, four types of questions must be answered:

- How do students approach graphing? How do they interpret the graphs they see?
- What issues does graphing raise for the design of curriculum in mathematics?
- What design considerations make for the most comprehensible, least distracting computer presentation and manipulation of graphs?
- How does the mathematics that students bring with them when they first encounter the computer graphing environment help them interpret it?

Refined versions of these questions have been the focus of the Algebra Group's research.

How This Focus Evolved: A Retrospective View

At the broadest level, the group began with an interest in whether multiple linked representation (MLR) software can "help" students. Software linking symbolic and graphical representations of function is proliferating very rapidly, and the claims about it are enticing. Both theory and common sense support the notion that MLR can aid understanding. Used thoughtfully, multiple representations increase redundancy and thus can reduce ambiguities that might be present in any single representation. Said another way, each well-chosen representation conveys part of the meaning best: together, they should improve the fidelity of the whole message. Finally, translation across representations can help to reduce the isolation of individual mathematical lessons and help to provide a more coherent and unified view of mathematical method and content. Many student errors may be directly traceable to the use of one or another representation system in isolation, where there is no ready "check" on the validity of actions taken (Kaput, in press).

As reasonable as these theoretical arguments are, it has been impractical to examine them clinically until the recent proliferation of software based on these ideas. In fact, very little is actually known about the cognitive impact of MLR in algebra. The nature of the impact, one must suppose, depends heavily on the nature of the software, including issues both of functionality and of interface design. While potentially reducing ambiguity, multiple representations give a student more places to look. Thoughtless software design may therefore be complicated and distracting.

When this group first proposed to study the effects of MLR on algebra learning, its members conceived of the research broadly as a two-part intervention study—teaching experiments in which students would work with selected software and curricula. The first part of the study, as they conceived it at the time, was to analyze how experience with suitably selected MLR software would affect certain well-known classes of algebra manipulation errors. This was to be done first, in part because it seemed to be a straightforward, focused, applied statistical study with a predictable (and relatively short) timetable and, in part, because it would likely yield data to help focus the second part. The second part planned to explore the impact of this qualitatively different experience with algebra on students' mathematical thinking.

The group decided to change its research plan after observing that when students were left alone to experiment, they induced rules that were misleading and limited in their applicability. This finding suggested that more research was needed to monitor *individuals* engaged in the tasks of interest. An intervention study focusing on statistical measurements of the performance of large numbers of students could be expected to miss essential features of student interaction with the software, features that would reveal *how* the software or curriculum succeeded or *why* it failed. It was important first to understand *how students develop the perceptual and semantic processes they use in interpreting graphical information.*

As the work progressed, the issue of how students understand scale became a focus. Scale issues are practically forced upon the student by the realities of computer graphing. Graphing is done in a space of certain dimensions: to graph within that space, one must choose a scale and an origin. Most classroom graphing that is done by hand on paper begins with functions that fit the paper "window" reasonably with little attention to scale issues. If scale must be considered on paper, the grapher controls it and probably knows what he or she wants soon after the first or second computation of the function's value. On the computer, things are different. If students are encouraged to explore freely to see what the graphs of various functions look like, the likelihood of their chosen functions fitting well in any fixed window is considerably lowered. There are two ways out: either the computer must choose a scale on which to display the graph, or the student must do so (perhaps with the aid of the computer). In both cases, for students to derive meaning from the visual presentation, they must understand the effect of the chosen scale on that image.

In working with students from eighth to twelfth grades, it became apparent that some aspects of scale are understood very early, while other aspects remain confusing even to some of the most sophisticated and mathematically successful students in precalculus and calculus. What seemed most interesting about these early results, however, was not the sequence in which scale ideas developed, but rather the complex interaction between strategies that students might develop for interpreting scale and other knowledge and strategies that they might have, including their general cognitive coding of perceptual features of the graph, their concept of variable, their understanding of the continuous nature of number (in particular, the continuous nature of the domain of the functions), their sense of a discrete point as representing a mapping of a single, selected input value to its image, and so on.

As a result, the group decided to continue exploring these related issues and to drop attempts to collect developmental data. The outcome of the first year of work thus became a "lay-of-the-land" view of the graphics-related issues that come up when studying algebra in a computer context (see Goldenberg, 1988a for a detailed discussion), and a strategy to help focus more narrowly on students' understanding of scale during the second year of research (Goldenberg, et al., 1988).

Year Five Research Activities

In its second year the group attempted to develop explanatory constructs for the students' overall problem-solving behavior in the context of the scale-related problems they presented. These constructs — the group calls them "metaphors" — endeavor to explain how students describe to themselves and to the researchers their ideas about the scale-related graphing problems posed.

New issues were raised, including in particular the visibility of pixels versus the invisibility of points, the characteristics of static media (e.g., paper) versus dynamic media (e.g., the computer screen) in graphing, and ways in which semantic distinctions between stretching a plane and stretching an image affect students' interpretation of scale change. These were discussed in detail in Goldenberg and Kliman (1988). The underlying issue that emerged most clearly from the data on students' problem-solving behavior in the context of scale-related problems was students' application of strategies they have built out of their everyday real-world experiences to the abstract visual world of graphed functions.

Methods

The group used clinical interviews throughout its second year of research.

All interviews — twelve with juniors and seniors taking mathematics at least at the pre-calculus level, and six with eighth graders taking first year algebra — were with bright and articulate students. They were selected deliberately to eliminate from the study, insofar as possible, results that could be attributed primarily to a particular student's gross disinterest or broad mathematical incompetence.

Five of the interviews were videotaped. The precalculus students in these interviews created functions on the computer using an experimental prototype of a program called *The*

Function Analyzer.[1] They observed the graphs, manipulated them in various ways (e.g., by changing the function or by changing the scale of the graph), and explained what they saw and did. Two video cameras, one trained on the screen and the other on the participants, recorded each interview.

Transcriptions of the videotaped interviews were heavily annotated with visual information about context (such as the state of the computer screen), writing or drawing that the student or interviewer might have done, typing, pointing or other communicative gestures, and other clarifications or supplements to the spoken parts of the dialogue.

The other thirteen interviews — five exploratory interviews with juniors and seniors on computer, two similar interviews off computer, and six interviews with eighth-grade students using worksheet material on various graphing issues—served as preparation, comparison, background, and follow-up data. Audiotapes of eight of these interviews were transcribed.

Results

This second year of research led researchers to infer three metaphors underlying students' words and actions.

- The *paper-and-pencil metaphor* is, at one level, a denial of dynamic scale change. As paper may be cut, graphs may be cropped, but stretching and shrinking are not natural operations if one thinks of graphs only as they exist on paper.
- The *magnifying-glass metaphor* is a concretization of dynamic scale change. It treats mathematical objects under magnification as if they were physical objects and allows them, therefore, to appear rougher or grainier when sufficiently enlarged.
- The *bead necklace metaphor* extends ideas of scale to points, which are unscalable. Students seem generally to regard points as extremely small, rather than as dimensionless; the attribution of any size whatsoever to points allows them to be conceptually magnified, lined up in a row, and so on.

1 *The Function Analyzer*, one component in *EDC's Algebra Series*, has since been published by Sunburst Communications, Inc. It allows users to explore relationships between symbolic expressions and their graphs by manipulating either representation and tracking the effect on the other. Students may freely mark reference points on the graph and may also create, edit, and study tables of values associated with their marked points, graphs, or symbolic expressions. Scale change, the issue explored in this research, can be accomplished either through a non-numeric stretch-shrink operation, or through explicit numeric setting of coordinate boundaries. For the purposes of this research, the group felt the latter command structure would give a richer picture of students' strategies, although it probably conditioned, in part, the kinds of responses that students gave.

These metaphors are of central importance because they served to focus, aid, direct, and misdirect students' explorations of graphs and to inform and limit their understanding of the mathematics behind those graphs. Each metaphor represents too brittle an extension into mathematics of ideas that suffice to explain a physical world. An exposition of these metaphors therefore became the major product of this group's work.

Conclusions: Implications for Curriculum and Software Design

1 Researchers must rethink the kinds of educational questions they ask about graphing. Not only does rapid graphing make new questions possible, but it makes *some* new questions, e.g., ones that draw attention to the possible ways of misinterpreting the newfound graphic information, quite important.

2 Students base comparisons of graphs on gestalts that they create by matching identifiable "special" points such as the vertex of the parabola. To help counter the attention that the vertex draws, software can let students mark points (e.g., the y-intercept) whose transformations they wish to track.

3 Language use deserves thoughtful attention. The constant term in a polynomial graph, determiner of the y-intercept, is often casually referred to as determining the "height" of a graph. Although this is often a convenient intuitive meaning for it, the two parabolas x^2+5 and x^2-4x+5 have the same y-intercept but appear to be graphed at different "heights," while x^2+5 and $(x-1)^2+5$ appear to be the same "height" but have different y-intercepts. Language being what it is, it would be unnatural (and probably ineffective) to proscribe the use of "height" as a description of the influence of the constant term, but the limitation should be made clear by drawing explicit attention to it.

In a similar vein, teachers and software developers must consider what metaphors language evokes and what metaphors to explicitly present. For example, describing scale change as "zooming in" or "looking through a magnifying glass" suggests not only an optical metaphor for scale change, but an unnecessarily (and often inappropriately) symmetric one. An optical metaphor might suggest that only the figure, and not the manifold in which it is embedded, is enlarged. By contrast, to describe rescaling as an action on graphs drawn on a rubber sheet is to draw attention to the action as a transformation of the whole plane itself. The difference appears to be important (Goldenberg and Kliman, 1988).

4 Optical illusions can affect the perception of graphs and cause misinterpretation of parallels, the direction of change, the shapes of curves, and other essential features. For example, any translation, including an $x \mapsto x$-a horizontal translation, of a function is generally perceived as a *vertical* translation if the function happens to be linear with absolute slope less than 1, and if it is graphed on a square screen. Similarly, any translation performed on a line whose absolute slope is *greater* than 1 is perceived as a *horizontal* move.

The functions x^2-$4x$+5 and x^2-$4x$+10 represent the same curve in two positions, one displaced vertically from the other. Yet, these curves may well be perceived as different shapes, the inner (upper) one appearing blunter.

Both of these effects may be reduced or eliminated if students gain experience shifting graphical objects around on the screen. When the pair of parabolas is produced by a *graphic* rather than symbolic manipulation — dragging one parabola vertically with a mouse or moving it stepwise with an arrow key — one is more apt to measure distances along the direction of movement than along a shortest path, and so the illusion can be expected to vanish. Similarly, when one watches the symbolic representation change as one graphically shifts the image of a line, one is more likely to associate the symbolic convention for recording a translation with the *direction of translation* — an unambiguous mapping — than with the end image which may be generated by an infinite number of different mappings.

5 Expressing a line as $mx+b$ emphasizes one set of relationships, while expressing it as $a(x-r)$ emphasizes another. Similarly, a parabola might be represented as ax^2+bx+c or as $a(x-r_1)(x-r_2)$ or as $a(x-h)^2+k$, or in yet other ways, depending on what features are to be emphasized. The *structure* of an algebraic expression may affect a student's interpretation of its graph, so multiple forms must be available for students to explore and translate among.

6 When multiple scales are used to represent the same graph, graphing windows should contain internal frames or other visual aids to help students recognize which portion of a distance view is being enlarged in a close-up view. See, in particular, figures 18 and 19 in Goldenberg (1988a) for examples of this kind of aid.

7 It is important that students have experience *controlling* scale. In fact, students need experience both with strictly metric controls (e.g., specifying the exact borders of the region of the plane they wish to examine) and with visual, primarily nonmetric controls (e.g., stretching or shrinking an image to reveal or match some property without having to compute window border values in x and y). Default behaviors of scaling controls (e.g., a zoom function of some sort) should support richer rather than poorer notions of the scaling of space. In particular, they should not reinforce students' apparent preferences for symmetry and linearity.

For a single example of an alternative conception of "zoom," at least for graphs of polynomials, one might decide that instead of operating exclusively in x-space in which horizontal and vertical stretching is the same, zoom should function in x^n-space, where n is the degree of the polynomial. In such a world "zooming out" on a linear function would expand one's field of view equally in both directions, just as we would normally expect, but "zooming out" on a quadratic would expand one's vertical view by the square of the factor by which the horizontal view is expanded. Conventional x-space zoom leaves a linear graph a_1x+a_0 looking more and more like a_1x as one zooms out, but leaves all higher order polynomials $a_nx^n+...a_2x^2+a_1x^1+a_0$ looking like vertical lines or rays as one zooms far enough out. By contrast, x^n-space would affect polynomials in a consistent way, making each appear more and more like the graph of its highest order term $a_n x^n$ as one zooms out.

8 Students using computer graphing, even at early stages, cannot escape having to deal with notions of continuous functions and discrete points, infinity and infinitesimals, the invisibility of points, and other issues usually ignored until calculus. Mathematics educators must consider appropriate ways of introducing these ideas much earlier than we typically do. The behaviors of some young students who become comfortable changing scales on graphs suggest they have an "intuitive calculus" long before they encounter the algebraic manipulations of formal calculus.

9 Computer experiences may allow students to form good mental images of graphs and scale changes and may also provide a meaningful context for them to explore their approaches to graphing and confront the limitations of these approaches. By contrast, reflective internalization of the computer experience may or may not be best achieved at the computer. It seems important to consider what blend of on- and off-computer activities provokes the most thoughtful integration of the two experiences into a coherent mathematical picture.

10 The most useful metaphors might best be introduced very early. For example, in dealing with scale, the motion of graphing on a rubber sheet and performing stretches on this sheet serves to clarify some issues that remain cloudy with the other metaphors. In anticipation of the rubber-sheet metaphor for the plane, the notion of a rubber number line might be introduced in elementary school at a time when the numbers between the integers are to be considered in greater detail, as when decimals are first being taught (see Goldenberg, 1988b).

Future Work

Successful use of the rubber-sheet metaphor requires a well-developed qualitative understanding of the results of changing scale, and this understanding logically bears on facility with the graphing software: at least some understanding of scale change is necessary to interpret and take advantage of the rapid scale changing and redrawing that the computer does so well, and to avoid the potential confusions resulting from inadvertent distortion. But to what extent does this qualitative understanding really transfer from one graphing medium to another? The Algebra Group's data suggest that computers and visual images may be so seductive that students abandon, at least temporarily, some of what they know about distortion and scale change in the face of a deceptive graph. If this is really so, research must investigate how to help students develop a more resilient and context-independent understanding of graphing and what would constitute such an understanding.

The group has identified several issues that bear on these questions. These issues form a general program for further investigation.

Sophisticated Approaches

The students with whom the group worked were among the best. Yet they exhibited what appeared to be deep confusions. At what level of knowledge or sophistication do these confusions not appear? Given that *some* language and gesture must be chosen in communicating about the problem situations, researchers, teachers, and software developers must be concerned that students' *thinking* may be more sophisticated than their *expressive style*. For example, the metaphors the group has constructed may reflect unfortunate choices of wording, as may the conventions of mathematics texts and teaching styles.

It would be most useful, in this regard, to know how knowledgeable and articulate teachers and mathematicians respond to the same problems posed to the students in this study. They would not be expected to be as confused by the outcomes as some of the students were, nor would they be expected to cling as tenaciously to incorrect explanations of the phenomena that they saw. But if their language and gesture were to suggest the same underlying metaphors, the group would have to conclude either that its construction of these metaphors is a poor reflection of underlying thinking about the problems and their elements or that using these metaphors is not, itself, a liability.

Imagery and Scale Change

This research suggests that it would be fruitful to investigate the kinds of images students use when working off the computer and how these images interact with those formed on the computer graphing screen.

In the group's studies, the off-computer students generated their own images, usually in their heads, very occasionally on paper. The on-computer students always had computer-generated images available. Mental imagery and computer graphing afford different kinds of control over images. The rubber sheet involves *intentionally* stretching and shrinking curves. Students using software may produce the same effects, but if, as was true of some of these students, they have wrong or confused ideas of what the effects mean, the stretching and shrinking may be perceived as a byproduct of some other intended change, and so may be partly *unintentional*.

What must the user know in order to take advantage of the control over images that the computer offers? For example, the students in the on-computer interviews knew enough to use the computer to focus in on areas of graphs but did not always know enough to avoid substantial confusion when this focusing significantly altered aspect ratio. Similarly, what must one know to use a mental rubber sheet successfully? The rubber sheet is helpful only if one can in at least a gross, qualitative way imagine a curve stretched and shrunk. To what extent does success depend on imagery abilities? To what extent does it depend on mathematical knowledge about curves and what they look like? By providing experiences with curves at different scales, can computer graphing software support the development of rubber sheet imagery?

How to Investigate the Use of Mental Imagery in Graphing

It is possible to observe directly how students use the computer as an aid to solving graphing problems (e.g., the type, sequence, and number of graphs they choose to create), but not how they use mental imagery. For example, students using the rubber sheet image seemed able to keep track of relationships between a "whole" curve and a relatively distorted portion of the same curve. How did they do this? Did they first mentally stretch the entire visible curve (as shown in the transition from figure 1a to 1b) and then zoom in on a particular region of the result (as shown in the transition from figure 1b to 1c)? Did they first select a region and perform the transformation on it alone? Such a technique would amount, in effect, to two stretches on the next-to-top quarter of the dotted box on figure 1a to render it the size of figure 1c. Did they imagine the graph drawn on a grid so that when it was distorted, the grid was distorted as well and could then be used as "standard units" in constructing graphs of different regions at the same aspect ratio (figure 2)? Or did they use some other imagery?

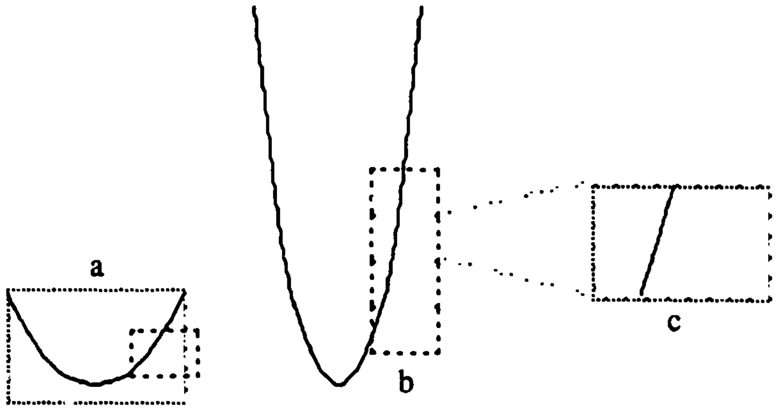


Figure 1

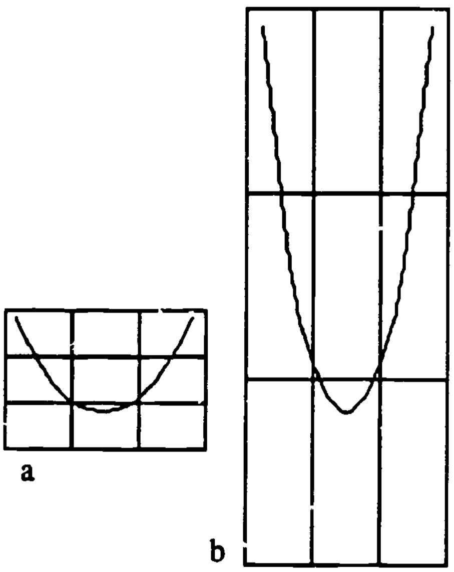


Figure 2

Some students may be able to describe the kinds of imagery they use in solving graphing problems. Furthermore, teaching experiments may help both to identify the nature of successful use of imagery in graphing and to explore ways of teaching such use to students. For example, one might present students with a particular way of visualizing scale change (e.g., the grid-square technique illustrated in figure 2) and then explore their subsequent approaches and misconceptions. Teaching experiments might also include presentation of different kinds of computer-generated images (e.g., a version of the graphing software with grid squares that reflected changes in aspect ratio).

Starting Computer Graphing with a Better Metaphor

How would explicit introduction of the rubber sheet metaphor — graph area on the screen as a window on a rubber sheet — interact with students' work on the computer? Is a click-and-drag rubber-sheet interface important, or does the language and imagery stand up to keyboard oriented interfaces like those implemented on *The Function Analyzer*? Would thinking of the screen in this way influence the way students use the software? For example, would they tend to do fewer on-screen scale changes (and perhaps more in their heads)? Would their predictions about the resulting changes in the graph tend to be more accurate? Would the way they interpret what they see on the screen change? Would they continue to invoke the paper-and-pencil metaphor? Would using the graphing software as a check on their mental manipulations (and as a tool for exploring a region in more accurate detail) lead students to develop a better understanding of the results of changing scale?

Navigation between a rubber sheet model and the kind of quantitative specification of scale information that the Agebra Group chose to have its computer students use necessitates translating between a qualitative and a quantitative representation. Would students find any advantage in performing (perhaps more rapid but less accurate) mental manipulations if they must then "check" their work by assigning coordinates to the portion of the rubber sheet they wish to see on the screen?

How would students fare if they interacted with software primarily or exclusively through qualitative manipulation of computer-generated images, for example, by using arrow keys or a mouse to stretch and shrink regions of a graph?

RESEARCH IN COMPUTING EDUCATION

OVERVIEW

ETC's computing projects have been concerned with the teaching of content in particular domains and with how instruction can be presented in a way that promotes transfer of learning to other domains. The Programming Group continued to test and refine its Prototype Metacourse, a ten-lesson intervention designed to be interspersed within a regular one-semester course in begining BASIC. The Metacourse provides mental models, problem-solving strategies, key concepts, and other structures to help students to understand more deeply and utilize more freely the knowledge they are acquiring during their regular instruction. While helping students to learn programming is the primary goal of the Metacourse, the group believes that the strategies and models the lessons present can be useful to students in other academic, professional, and life areas. Thus, in this year's refinements of the curriculum, the group focused explicitly on how to promote such transfer. In addition, the group believes that the metacourse format — a group of lessons designed to amplify, not replace, a given course — has promise not only for the teaching of other programming languages, but for instruction in other content areas.

The Systems Thinking Group has focused even more directly on how technology can promote higher order thinking skills that are transferable across domains. This group has studied the use of STELLA, an example of simulation modeling software, to teach a variety of subject matters in the physical, biological, and social sciences. This research focuses both on students' learning of content knowledge in courses infused with a systems thinking perspective and on students' growing understanding of systems thinking itself, as a tool that can be applied to many areas of learning. Like the Programming Group, this group's approach is designed to be integrated into existing courses, not to replace them.

PROGRAMMING

Steven Schwartz, ETC/University of Massachusetts, Amherst, Project Leader
D.N. Perkins, ETC
Greg Estey, ETC
John Kruidenier, ETC
Rebecca Simmons, ETC
Suman Bhattacharjea, ETC
David Niguidula, ETC
Julie Taminiau, ETC
Shelagh Turner, ETC

Through clinical studies and teaching experiments the Programming Research Group has sought to understand better the factors that interfere with beginners' mastery of programming in BASIC and LOGO and to devise instructional methods that enhance their learning (Perkins, Farady, Hancock, Hobbs, Simmons, Tuck, & Villa, 1986; Perkins, & Martin, 1986; Perkins, Hancock, Hobbs, Martin, & Simmons, 1986; Perkins, Martin, & Faraday, 1986; Perkins, Schwartz, & Simmons, 1988).

The Difficulties of Novice Programmers

The group's early clinical studies, consistent with most of the literature, (Mayer, 1981; Bonar, & Soloway, 1985; DuBoulay, 1986) indicated that many students had considerable difficulty in achieving even the most rudimentary mastery of the precision-intensive, design-intensive, and problem solving-intensive programming subject matter. While it was not the case that students had no relevant knowledge, the group found a range of student difficulties that may be characterized as falling under three broad headings: fragile knowledge, a shortfall in elementary problem-solving strategies, and problems of control and confidence.

"Fragile knowledge" refers to students' common display of programming knowledge that is partial, inert (not evoked in contexts of need but retrievable with cueing), and garbled (concepts used in the wrong place, in inappropriate hybrids). Because students typically have much more knowledge than they use well, the group hypothesized that if they could somehow activate their inert knowledge and perform internal crosschecks of garbled knowledge, they would perform substantially better.

Regarding problem-solving strategies, clinical experiments reported in Perkins, Hancock, Hobbs, Martin, and Simmons (1986) and Perkins, Martin, and Farady (1986), indicate that students rarely ask themselves such elementary problem management questions as "What am I trying to do now?" "Do I know a command that could help?" and "Exactly what does the line of code I just wrote do if I hand execute it?". The group hypothesized that better elementary problem-solving and metacognitive strategies could help students make better use of their fragile knowledge base.

Finally, students evince motivational problems that interfere with their control of their own problem-solving processes. For example, many students simply disengage from programming problems and commence a side activity or seek help as soon as the smallest difficulties emerge. Although these "stoppers," as the group has called them, do not seem to recognize their own abilities, they are often quite capable of continuing on nondirective prompting (Perkins, Hancock, Hobbs, Martin, & Simmons, 1986).

The group's research along with others' (Bonar & Solway, 1985; Pea, 1986) also indicated that many students have an animistic conception of the computer as somehow "knowing" what the programmer intends. Their difficulties in hand executing programs further indicate a poor mental model of what the computer does. As a result, their inferences about why errors occur and their conjectures about how to fix them are generally inadequate.

The Metacourse: Its Purpose and Design

These observations led to the development of an eight-lesson "Metacourse" created specifically to address these targets of difficulty. The Metacourse is a series of lessons and modules designed to provide a small number of key concepts and strategies which research has shown only a small number of students acquire on their own. As its name suggests, the Metacourse can be thought of as transcending the content of regular instruction to provide programming-specific skills and a conceptual framework to guide the exploratory thinking of the novice programmer. It offers a mental model of the computer and how it works, presents strategies for understanding and relating commands to that model and for breaking down complex problems into subproblems, and stresses concepts and tactics to help students deal with the difficulties characterized in earlier research. Among the key concepts and heuristic strategies introduced in the Metacourse are: a mental, highly visual model of what happens inside the computer; an analytical scheme for comprehending commands and command lines in terms of their "purpose," "syntax," and "action"; and a set of heuristics and resources for generating and debugging programs.

The intervention is organized so teachers can introduce key concepts at intervals, "infusing" them into the regular curriculum as the term advances and students gain in knowledge of BASIC. It differs from conventional attempts to redesign curriculum by the process of infusion, by its metacognitive emphasis, and by merging with, not displacing, an existing course, thus lending itself more easily than other efforts at curriculum reform to wide dissemination. The group made a conscious choice to design an intervention with significant chances of achieving success (the BASIC Metacourse) in addressing directly the targets of difficulty students encountered in programming, rather than to concentrate on the development of sophisticated technology. Thus, an animated computer-based model of the computer (called the "Data Factory") was developed only later as a complement to the other Metacourse materials.

The concept of a mental model was key in the design of the Metacourse. Recent work in the field of cognition and the pedagogy of computer programming underscored the importance of helping students construct robust models (Gentner & Stevens, 1983; Falmagne, 1975; Beveridge & Parkins, 1987; Mayer, 1985; Kurland, Clement, Mawby, & Pea, 1987). The model the group developed (initially referred to as the "paper computer" and later revised as the "data factory") visually depicts variables and their values, characters on the screen, and the flow of control and information in the computer. Presented on overheads and posters, as well as dynamically on software, this model shows requisite changes in the computer states as a "n awfully bright" robot (NAB) executes the comands on each line of the program. The data factory offers students a mental model of the machine through which they can represent to themselves the effects of command execution and thus aid their understanding of exactly what commands d

To further enhance their understanding of computer programs, students also learn an analytic scheme for comprehending commands and command lines in terms of, (1) the purpose of a command, (2) its legal syntax, and (3) its action in the computer world as shown in the data factory. Teachers are encouraged to present, and students to utilize, this framework as a way to organize their learning of each new command. The Metacourse also emphasizes the utility of employing the purpose-action-syntax framework when trying to understand the lines of a program during checking and testing of program parts or whole programs. These concepts in effect provide students with elementary self-prompts, or metacognitions, tuned to the programming context, that add to their repertoire of elementary problem-solving strategies. Such self-guiding and self-monitoring heuristics should help them in learning to program, as it has helped improve student performance on other cognitive tasks (Bereiter & Scardamalia, 1986; Palinscar & Brown, 1984; Schoenfeld, 1987; Larkin, 1987, etc.)

In addition, the Metacourse enables teachers to provide students with a number of metacognitive and metaconceptual heuristics and with resources to help them understand and generate BASIC programs. The problem-solving nature of comprehending and producing programs, involving multiple rounds of modeling, planning or conjecturing, writing code, debugging or inferencing, further conjecturing and testing is emphasized. In order to further facilitate the acquisition of these difficult programming skills, teachers introduce students to:

(1) the concept of frequently occurring lines or chunks of code that work together to accomplish a particular job. The Metacourse calls such recurrent schema "patterns" (i.e., a summing pattern, a counting pattern), a term roughly synonymous with the "programming plans" described by Soloway and colleagues (Soloway & Ehrlich, 1984). Lessons stress the importance of patterns for efficient comprehension of programs and program segments as well as their utility and portability in the construction of programs.

(2) specific heuristics to employ in generating and debugging programs. These serve as aids in moving from a given problem statement to the initial stages of task decomposition, generating code, classifying, locating, and correcting the inevitable bugs that occur in programs. Again, the emphasis is on programming as a problem-solving activity involving cycles of venturing reasonable hypotheses about how to decompose the problem statement into a series of actions for which BASIC commands are available, testing these hypotheses in the form of a BASIC program containing proper syntax, inferring the nature and location of bugs from the programs' output, conjecturing corrections, testing these, and so on, until success is achieved. While the task may sound formidable, students are assured that they have available a considerable arsenal of powerful heuristics and resources to call upon.

Metacourse materials also include:

(1) a "minimanual" of quick, easy-access BASIC commands presented in the purpose-syntax-action framework, accompanied by examples. The minimanual is designed to help the student overcome some of the initial information overload associated with learning a programming language. Seven common "patterns" also appear at the end of the minimanual.

(2) A set of four large posters constantly on display in the computer room, depicting the data factory, the purpose-syntax-action framework, strategies for program generation and debugging, and a general "toolbox" of prompts and heuristics to use at various times when encountering difficulties in the programming enterprise. These posters are designed to help keep the major ideas of the Metacourse salient and in use long after their original introduction.

Classroom Studies of the Metacourse

Although the Metacourse in BASIC was first pilot tested in the spring of 1986, it was not until the fall of that year that a large scale test with over 300 students in some 17 different high schools was conducted. The results of that study, reported in detail in Schwartz, Perkins, Estey, Kruidenier, and Simmons (1987), were quite positive. The Metacourse's impact, as evaluated by a fairly conventional test of comprehension, hand-execution, debugging, and program generation, was considerable. Students who used the Metacourse gained about half a standard deviation more overall than students in the control groups, with gains on different problem types ranging from one-third to two-thirds of a standard deviation. While the Metacourse stressed mastery of BASIC rather than transfer to general cognitive skills, significant "near transfer" was observed in the experimental groups on a task that closely resembled programming (formally describing a series c actions in a story in terms of a sequence of "repeats" and "decides").

The experimental groups in this study came from high schools which had agreed to participate in an intensive laboratory site research and implementation experience, involving considerable support for teachers directly involved in testing curriculum materials. Therefore it was possible that the gains observed might have been attributable primarily to the extraordinary level of support provided teachers and not to the Metacouse itself. Thus it was quite reassuring when nearly identical results were obtained the following spring with a new group of students whose teachers received minimal training or support.

The instructors in the spring study received a two-hour introduction to the philosophy of the BASIC Metacourse along with the eight-lesson package. The only other support they received took the form of two-page "Metacourse Memos," one for each lesson, containing teaching tips gleaned from the instructors who had used the Metacourse the previous semester. These "memos" were mailed to the instructors prior to the presentation of each lesson. As shown in Figure (1), the teachers in this study were able to elicit performances from their students on a variety of types of BASIC problems that came very close to those obtained in the previous study where teachers had more extensive supports. This evidence suggests that the Metacourse in BASIC can provide teachers with a powerful pedagogy for improving student performance, without requiring extensive faculty development time.

Revisions of the Metacourse

While the results cited above were quite encouraging, the group observed some problems. Many teachers objected to the relative lack of freedom inherent in the fully documented discourse-type lessons provided in the original Metacourse, indicating that they would welcome shorter materials that allowed more teacher discretion. The group had also observed that although teachers generally infused certain major concepts from the Metacourse into their regular lectures (i.e., stressing the purpose-syntax-action of each new BASIC command), many important concepts and heuristics received little mention after they were introduced.

Thus during the summer of 1987 the group responded to these classroom observations and teacher interviews by undertaking a major revision of the BASIC Metacourse. These revisions took the form of changes in style and additions to its content. A modular, packet-type format was developed to provide teachers with more freedom to present their own methods and examples of the Metacourse concepts. Four new packets were designed to help teachers *infuse* specific concepts and heuristic strategies throughout the course.

Finally, the group's observations of teachers and students had indicated that examples geared to promoting transfer of general concepts presented in the Metacourse to other academic, professional, and life areas almost never came up in programming classes, even though teachers reported this as one of the major goals they hoped to achieve in their

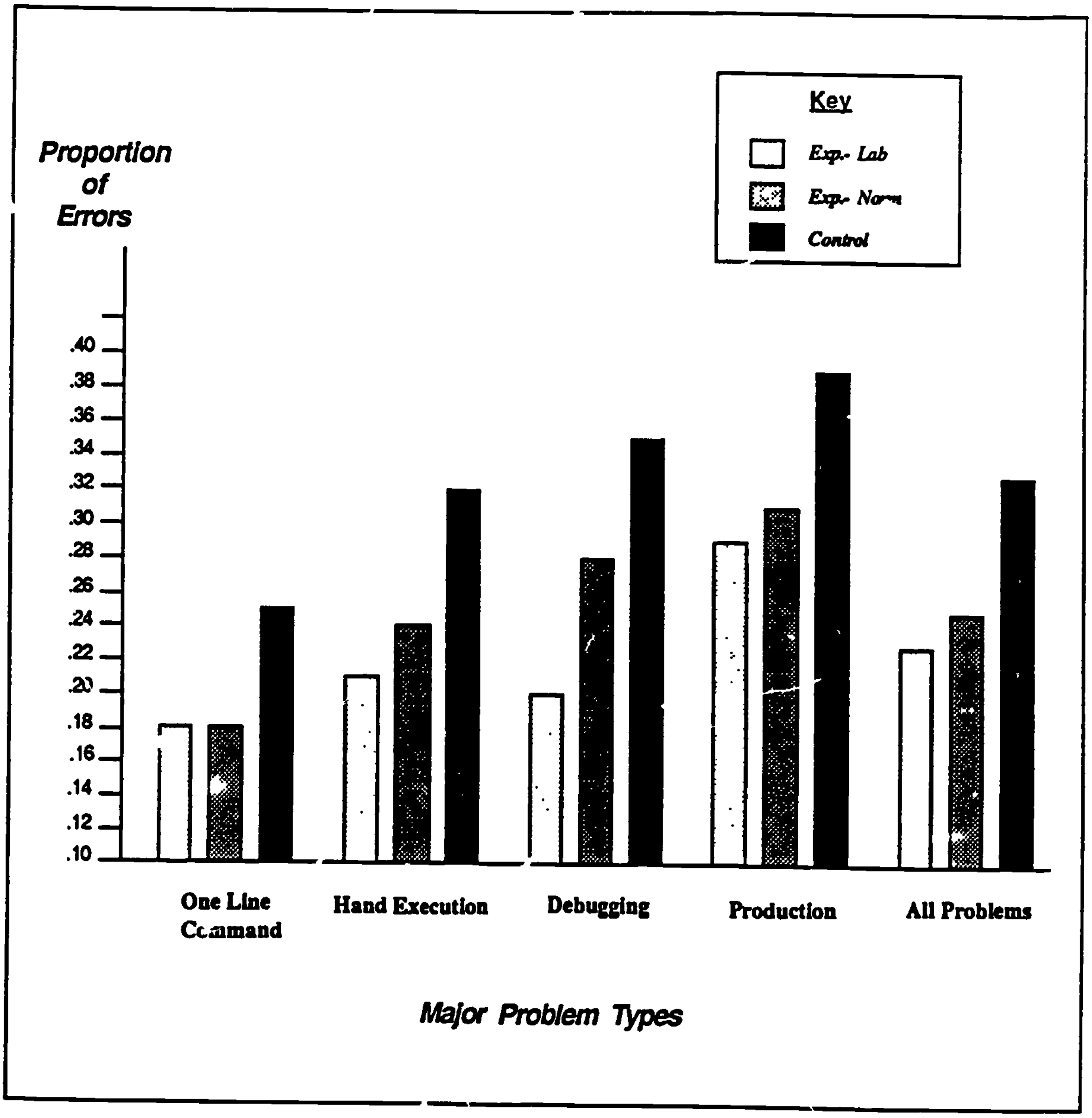


Figure 1: Differences in Errors (Mean Proportion) of One Control and Two Metacourse Groups on Major Problem Types in the BASIC Test.

courses. To address this minimal attention to transfer (and the minimal evidence of it on end-of-semester tests), the group went on in the fall and winter of 1987-88 to develop three more packets with the specific purpose of promoting transfer. These packets demonstrated the utility of models, imaging, and debugging strategies respectively. They were completed too late to be included in the quantitative evaluation of the Metacourse but were presented in three BASIC classrooms in the spring of 1988.

A pilot study of the BASIC Metacourse in packet format was conducted in the fall and spring of 1988, with 5 teachers and more than 120 students in three high schools. The quantitative data from this study yielded some unexpected results. The performance on the end-of-semester BASIC test of the classes that used the newly developed packets not only did not match previous results with the original "scripted" Metacourse, but in fact was significantly poorer than the performance of control groups. While data from the general cognitive skills pretest indicates that the new experimental group was slightly lower in ability than the control group, this in itself was not a sufficient explanation for the poor showing of the experimental students. Analysis of Covariance confirmed the poor performance of the experimental groups.

The group's interpretation of this finding focuses on two major differences between the scripted and packet formats. First, the scripted version required considerable student practice on problems through explicit class exercises and homework problems. Such work was only suggested rather than prescribed in the packet Metacourse, leaving the teacher responsible for providing the problem examples. Thus, the group believes that *these students simply practiced on fewer problems*. Second, the scripted version, by design, required little preparation by the teacher prior to presentation; much of the materials could be read verbatim, with all relevant exercises provided. The packet version provided instructors with more freedom, but it also demanded much more of them to make the lessons go well. Thus, a typical packet required teachers to come up with their own examples, exercises, and homeworks assignments to reinforce the objectives of that lesson. The group believes that *this version of the Metacourse placed too heavy a demand on most instructors and thus their presentations to students were ineffective.* While teachers often speak of the desire for more freedom to innovate, the normal day-to-day demands of teaching make it difficult for them to take advantage of such freedom. Thus, such innovations are often not successful, at least until teachers have had more time and experience with the new materials. Given the limited resources available for inservice training, a scripted version of the Metacourse, or a packet version that is more directive and demands less intensive preparation, appears more likely to succeed.

The group has begun an extensive revision of the packet Metacourse in order to test these hypotheses with a packet version that it believes could yield results comparable to those obtained with the scripted version. These revisions involve simplifying the organization of the Metacourse and adding explicit class exercises and homeworks. Under the organization currently planned the first teaching "cycle" of the Metacourse would contain only two packets, one introducing the "data factory" model and the other introducing the "purpose-syntax-action" procedure for analyzing commands A second cycle would present a number of simple heuristic strategies for producing and debugging programs. A third cycle would follow with further strategies for programs of greater size. A final optional cycle would contain the three recently developed "transfer packets" that focus on the utility of mental models, imagery, and debugging strategies for problem-solving in other academic disciplines and areas of life. The last three packets were tried recently in single classes and elicited positive qualitative reactions from both teachers and students.

Simultaneously, the group has edited and supplemented the scripted Metacourse to include the more complete "data factory" model with its "NAB" and to provide disks for demonstration of the "animated data factory." This contrasts with the earlier scripted version which contained a somewhat less elaborate "computer world" without the dynamics of a "NAB." Also, the scripted lessons on program generation and debugging (6a and b) were revised substantially because teachers had indicated they were too long and complex.

General Conclusions on the Major Research Questions

The Programming Group began its research with the hypothesis that teachers, through modest training, could instill in their novice students a small number of key metacognitive strategies which would have significant impact on student's programming performance. Early clinical research confirmed the "fragile knowledge" of many programming students and helped direct the group to the metacognitive strategies that might improve performance. These strategies form the core of the BASIC Metacourse.

The Metacourse offers a mental model of the computer and how it works, presents strategies for understanding and relating commands to that model and for breaking down complex problems into subproblems, and stresses concepts and tactics to help students deal with difficulties characterized in earlier research. The intervention is organized so teachers can introduce key concepts at intervals, "infusing" them into the regular curriculum as the term advances and students gain in knowledge of BASIC. The results of two large-scale empirical studies indicate that the BASIC Metacourse is an intervention programming teachers can readily adopt and incorporate into their normal instruction, even without extensive training and support. While modest in scope, this "vitamin shot" is likely to produce significantly better mastery of BASIC among their students.

Beyond this overall and highly encouraging finding, there are several questions to which the current research provides only partial answers. These questions have to do with the transfer of cognitive skills from one domain to another, with the Metacourse format that best suits teachers' needs and promotes smooth and effective implementation, and with the modification of the Metacourse for use with other programming languages.

Transfer

For teachers, the notion of combining instruction in programming with instruction for transfer of general cognitive skills has been a contradiction. While most teachers state that one of the primary values they see in teaching BASIC or LOGO is the development of general thinking and problem-solving abilities, observations of programming classes indicate that almost no time is explicitly devoted to promoting transfer. Not surprisingly, despite the lofty ideal, sometimes encouraged by programming language developers (Papert, 1980), the literature indicates generally negative results. The rare exceptions involve either near transfer (Clements, 1985; Clements & Gullo, 1984), or intensive one-to-one teaching environments (Linn, 1985). The Programming Group's research replicates these findings (Schwartz, Perkins, Simmons, Kruidenier & Estey, 1987) with evidence of transfer only to the task most related to programming (the "repeats and decides" task) and only where transfer was explicitly discussed and encouraged by teachers. In general, teachers spend little time explicating bridges between programming strategies and other subject matter.

There are good reasons why programming teachers spend almost no time teaching for such transfer. Most of their students have a hard time mastering even the basics of programming in a semester or two, and virtually no available materials provide explicit models for such teaching. To fill this need, the Programming Group developed three "outbridging" or transfer packets in the spring of 1988. These packets focus on three heuristic strategies embodied in the BASIC Metacourse that the group felt had widespread applicability to problem-solving in other programming languages, academic subjects, professional and general life situations. The three topics are "the power of modeling or representation," "the power of mental imagery," and"the power of debugging strategies." In each case, the packets review strategies students have used in their BASIC programming and generalizes these to other areas through numerous examples and exercises to be infused into the normal BASIC programming course.

As indicated previously, these packets received positive qualitative reactions during pilot testing, but hard evidence concerning their effectiveness is not yet available. In addition, the group still questions whether this format is optimal since a strong case can be made for facilitating transfer in two directions: not only can concepts and heuristics used in programming be applied to other content areas, but models that students are already familiar with in other subject areas might facilitate the introduction of concepts in the programming context. For example, familiarity with models or representations of the flow of electric current in terms of water flowing in pipes might facilitate students' introduction to the "flow" of information in a "data factory" as a model of what happens inside a computer. This link should result in faster and more integrated acquisition of the "data factory" model since the new concept will connect to a rich cognitive network already established in the student's long-term memory. This line of argument suggests incorporating such analogies directly into the packets which introduce such concepts and strategies in the BASIC Metacourse, rather than presenting them in special "outbridging" packets to be introduced later in the term. The group expects that additional research with these materials will clarify this interesting pedagogical question.

A related problem within the field of cognitive psychology is the lack of good measures of transfer. While the literature contains numerous assertions about which general cognitive and/or affective skills might benefit from instruction in programming languages (Salomon & Perkins, 1987; Soloway, Lochhead, & Clement, 1982; Linn, 1985; Papert, 1980), there is little agreement on how these skills should be assessed. The cognitive skills instrument the programming group developed in its research contained a number of subtests theoretically related to skills and attitudes developed in programming but was designed primarily as a measure of general cognitive abilities to be used in equating groups prior to treatment. Thus, this instrument was far from an ideal measure of transfer. The development of a more sensitive and broader measure of transfer would benefit the field in general.

Directiveness of Metacourse Materials

As indicated previously, a pilot study employing an initial version of the BASIC Metacourse in packet format yielded results quite different from those observed with the scripted version of the Metacourse. Based on these results a revised version of the Metacourse in packet format has been developed which incorporates the successful elements of both the scripted and the packet versions. Though the scripted version enjoyed relative success, a number of teachers have indicated a discomfort with the lack of freedom inherent in the scripted format. Empirical studies which compare the effectiveness of the more directive scripted version of the Metacourse with the less directive packet version are clearly needed.

In addition to the procedures already designed to assess performance of students and teachers (i.e., general cognitive pre/post tests, the BASIC performance test, observations of a portion of class sessions), the group needs further indices of professional development, perhaps utilizing some of the criteria and measures developed within the LOGO programming environment Watt, & Watt, 1988). The group expects to find interactions between the degree of optimal directiveness of Metacourse materials and teachers' professional background, educational ideas and values associated with teaching programming, classroom and teaching situation, and opportunity to prepare new materials. More basic research on these questions is needed before offering reasonable prescriptions for the optimal form of Metacourse materials.

Development of a Metacourse for Other Programming Languages

If the ideas embodied in the BASIC Metacourse are as general as the group thinks, then it should be possible to develop a comparable Metacourse for other programming languages. The two most likely candidates are LOGO and PASCAL, since these, along with BASIC, are the languages most often taught in primary and secondary schools. While either would be possible, the Programming Group feels that LOGO would be preferable for a number of reasons. Not only is it a language quite different in structure from BASIC, but widespread claims have been made for its beneficial effects on students thinking and attitudes regarding mathematics, physics, and problem-solving in general (Papert, 1980; Watt, 1982; Watt & Watt, 1986). While the claims have far exceeded the actual results reported in the literature (Kurland et. al. 1985; Pea et. al. 1987, Moursund, 1983), positive transfer has been obtained in a few cases under rather special teaching conditions.

Perhaps more important is the fact that LOGO, normally taught in primary school, is the first computer language most children learn. The group feels this would be an optimal period to infuse the powerful metacognitive and metaconceptual principles inherent in a Metacourse Children of this age group may well be particularly suited to the highly visual, iconic presentation incorporated into the design of the Metacourse. If students were to assimilate some of these problem-solving heuristics early in their academic careers, they might have much greater impact on future learning of programming languages, on how students think about computers, and even on their learning in other disciplines.

Thus, the group would like to build on its work in BASIC and its earlier work with younger children with LOGO (Hancock, Perkins, & Simmons, 1985) to develop a metacourse in LOGO, emphasizing the principles that have been effective in the BASIC Metacourse. Clinical work with students as they attempt to solve LOGO problems should be followed by the design and pilot testing of an initial version of the LOGO metacourse with teachers who are part of a collaborative team. The metacourse could borrow heavily from the concepts and heuristics employed successfully in the BASIC Metacourse (i.e., the data factory, the purpose-syntax-action framework) but be adapted to the challenges of teaching this age group and the specifics of the LOGO language. An animated software version of the actions taking place within the data factory could be developed, borrowing heavily from the group's experience with BASIC.

The LOGO metacourse could then be revised and subjected to an evaluation in a number of classrooms with teachers who are not part of the ETC collaborative. This summative evaluation, would employ a pre/posttest design with participating classrooms randomly assigned to treatment (Metacourse used) and control (Metacourse not used) conditions. As with the BASIC research, the pre/posttesting should include a test of general cognitive ability, administered to all participants to check against treatment-control group equivalence, to provide a covariate, and to incorporate measures of near and far transfer. A subtest of this measure would consist of an assessment of attitudes toward problem solving and errors, since there has been speculation that such changes would occur as a result of LOGO experience (Papert, 1980; Zelman, 1985). For posttesting only, a test of LOGO mastery would be administered. Superior performance in the treatment group would validate the general metacourse approach across different programming languages and different age children.

The final stage of this research would involve the revision and packaging of materials for broad dissemination. The aim would be to make the Metacourse a robust instructional intervention that can improve instruction independent of any contact with the developers, relying primarily upon the materials themselves, with only minimal inservice training or support.

SYSTEMS THINKING

Ellen B. Mandinach, Educational Testing Service, Project Leader
Nancy L. Benton, Educational Testing Service
Hugh F. Cline, Educational Testing Service
Margaret E. Thorpe, Educational Testing Service

The ETC Systems Thinking Project, which conducts the Systems Thinking and Curriculum Innovation (STACI) Project, examines the cognitive demands and consequences of learning from a systems thinking approach to instruction and from using simulation-modeling software. Based at Educational Testing Service, this project tests the potentials and effects of using the systems approach in existing secondary school curricula to teach content-specific knowledge as well as general problem-solving skills. The research examines the effectiveness of using STELLA (Structural Thinking Experimental Learning Laboratory with Animation; Richmond, 1985), a simulation-modeling software program, as a tool to teach system dynamics and content knowledge. It focuses on the teaching and learning outcomes and transfer that result from introducing a software environment that enables students to make and learn from concrete multiple representations of scientific, mathematical, and historical phenomena. The research also focuses on the organizational impact of introducing a technology-based curriculum innovation into the school setting.

The Target of Difficulty and an Approach to It

A primary focus in the STACI Project is the study of students' development of higher-order thinking skills. The group has investigated this complex aspect of learning within the context of an effort at Brattleboro Union High School in Brattleboro, Vermont, to use systems thinking in the teaching of science and social studies. There, the group's research has focused on students' cognitive processes and learning outcomes and on the instructional strategies and processes that lead to knowledge and skill acquisition.

Educators and researchers hope that higher-order thinking skills are teachable and transferable. Numerous instructional programs have emphasized the development of skills deemed critical to general intellective performance (e.g., Feuerstein, 1979, 1980; Palincsar & Brown, 1984), and Voss (1978) notes that transfer is central to all learning. Nevertheless, not all learners are equally likely to transfer skills from one domain to another. Nor is it clear whether there exist certain cognitive skills that facilitate transfer and whether and how such skills are themselves teachable or transferable across domains.

Further, while such general processes are considered important, they are not thought to be sufficient to produce learning (e.g., Resnick, 1987). Rather, many researchers and theorists agree that they must be embedded within a content area that provides an appropriate environment in which to cultivate and apply the higher-order skills. Uncertainty continues as to the appropriate balance and relationship between the acquisition of content (declarative) knowledge and procedural knowledge.

The systems thinking approach, although not a skills training program per se, is regarded as a general problem-solving tool that can be implemented flexibly across content areas and integrated into existing courses. As a scientific analysis technique, systems thinking is used primarily for its heuristic value. This approach, which emphasizes the creation and manipulation of models, is increasingly recognized as a potentially powerful teaching technique that helps students construct mental representations of a subject.

In this study, the systems perspective has been embedded in physical and social science curricula to provide contexts within which to assess the acquisition of content knowledge and higher-order thinking skills. Cognitive analyses (see Mandinach, 1986) have identified skills that underlie successful performance in systems-infused courses. The integration of systems thinking into existing courses satisfies Resnick's recommendation that thinking skills be embedded into content areas rather than taught separately. This integration also allows exploration of how technology-based curricula can be implemented in such a way as to augment and enhance existing course materials. It also addresses issues of classroom management and instructional procedures created by the use of technology: how computers can be used in classroom settings.

Systems Thinking

System dynamics is a tool for understanding the behavior of complex phenomena over time. Based on the concept of change, system dynamics uses simulations and computer-based mathematical models to represent complex relationships among variables in the environment (Forrester, 1968). By incorporating the rules that govern change within a system, these models show the interactions among variables and allow examination of cause-and-effect relationships. The notion of a system assumes that (a) all systems have variables (inputs and outputs) that change over time, (b) these variables are interconnected by cause-and-effect feedback loops, and (c) a change in the status of one or more variables subsequently affects the status of other variables.

In systems thinking, simulation models, simplified representations of real-world systems over hypothetical time, are used to examine the structure of systems. Using simulation software, characteristics of selected variables can be altered and their effects on other variables and the entire system assessed. To build a simulation, it is necessary to understand the major variables that comprise the system. These variables are used to form a dynamic feedback system, expressed in terms of simultaneous equations. That is, over time, variables change and subsequently cause other variables and their interactions to change as well.

STELLA

The concepts that underlie the field of system dynamics form the basis for much of the simulation software that currently is used in educational settings. Until recently, the instructional use of systems thinking was constrained to environments that had powerful mainframe computers. The advent of a software product, *STELLA*, recently has made it possible to operationalize these concepts on a microcomputer. *STELLA* capitalizes on the graphics and icon technology of the Macintosh microcomputer (several windows — structural diagrams, equations, graph pads, tables — are available to the learner), thereby enabling individuals not versed in the intricacies of mathematical modeling to create their own systems. By minimizing the mathematical and technical skills needed to construct models, *STELLA* facilitates the creation and manipulation of complex models of system phenomena. *STELLA* facilitates students' introduction to the analytic and problem-solving perspectives inherent in systems thinking through an iterative process of simulation model construction. Such model-building requires learners to formulate, test, and revise hypotheses about relationships within the dynamic systems.

With *STELLA*, modeling now can be incorporated into science, mathematics, and social studies education at the secondary level. Recently the Mathematical Sciences Education Board (1987) and the National Science Board Commission on Precollege Education in Mathematics, Science, and Technology (1983) recommended that modeling become a major emphasis in mathematics and science education. Because the costs of the Macintosh and

STELLA now are affordable for many secondary schools, it is possible to implement the Board's recommendation on a wide-scale basis.

STACI Project Design and Results

The study was conducted at Brattleboro Union High School (BUHS) where four teachers used the systems perspective in their courses, including general physical science (GPS), biology, chemistry, physics, and an experimental course on War and Revolution. The four teachers, trained to use *STELLA* and system dynamics, used models, illustrated them on the computer, and integrated them in their classes at varying levels of complexity and sophistication. In the project's first year, 172 students were enrolled in the systems science classes, while 181 students were in the traditionally taught control courses. In the second year, 252 students were in the systems classes, and 244 in the control classes. Two substudies also were conducted: an intensive case study of the War and Revolution seminar and an organizational case study of the curriculum innovation's impact on the school.

Instrumentation

Several types of instruments, including pretest, in-class, and posttest measures, were used to assess outcomes in various stages of the research. Initial assessments of subjects' ability, content-specific knowledge, and systems thinking were used. Standardized achievement test scores and a small reference battery served as rough estimates of general ability and higher-order thinking skills. Previous final examinations in the sciences were modified and administered to both systems and traditional classes. These tests served as baselines of content-knowledge in the subject areas. An initial assessment of systems thinking also was administered to serve as a baseline for the experimental classes. Teachers administered content-specific tests in their courses throughout the academic year, thus making possible examination of differences in content knowledge in the systems and traditional courses. An additional measure of systems thinking was developed to assess end-of-year knowledge of concepts emphasized in the instruction. The test focused on concepts such as knowledge of graphing, equations, variation and variables, causation and causality, feedback, and looping constructs. Posttests of content knowledge and general problem solving were administered.

The Science Curricula

An integrative approach was used in the science courses, where the classes covered the same body of knowledge taught in traditional science curricula, but discussions of selected concepts and topics were supplemented with a systems perspective. In these courses, students learned concepts underlying model development and experimented with existing models using *STELLA*. Each of the science teachers adapted the systems approach to their courses in a different way, reflective of the particular content areas. The modeling activities generally took two forms. Depending on the course, students either developed their own models of scientific phenomena or used models they were given and altered particular parameters to examine the subsequent effects on the entire system.

In GPS, the teacher introduced systems through the graphing of cause-and-effect relationships and use of simple arrow diagrams within the context of several topics (e.g., motion, magnetism). The concept of modeling was a recurrent theme throughout the course, with simple mathematical models developed to illustrate many concepts.

Biology lent itself most readily to a systems approach. Because the interrelationship of living systems is a key concept in biology, systems thinking could be applied in many areas. Students were introduced to the fundamental principles of systems, modeling, feedback, and causality. Modeling was integrated throughout the course, with presentations of models on topics such as oxygen production, metabolism, and population Students worked on models that the teacher constructed and manipulated parameters within a guided learning format. Laboratories generally were connected to the presentation of a model. Students formulated and tested hypotheses within the context of a traditional laboratory experiment as well as by simulating results with *STELLA*.

Chemistry was a more difficult course into which to integrate systems thinking. The teacher found the most appropriate topics (e.g., relations among rates, time, and levels) and focused the approach there. Students were guided to develop systems models for chemical reactions. Structural diagrams and models provided instructional tools not only to illustrate the functions of and relationships among certain variables, but to hypothesize and then test changes in behavior of these variables under different conditions over time. From these guided inquiry experiences, a generic understanding of the behavior of a set of interacting variables was developed. The chemistry teacher adapted typical textbook problems for use in systems modules. He also constructed numerous worksheets which students answered using systems thinking. The approach to these problems was to help students learn that problem solving is an iterative process of testing, revising, and retesting hypotheses. The problems often included a series of "what if" situations; that is, students were asked to hypothesize what would happen if certain parameters in a problem were changed. Students provided a rationale for their hypotheses, then tested them by constructing models and running them over simulated time.

The physics course, in which the systems approach was introduced in the project's second year, used a similar approach. Standard textbook problems were solved using systems thinking as well as traditional techniques. With the systems approach, students were asked to design a model of the problem, run the model with STELLA, and test out various parameters. To solve problems in a traditional manner, they worked through the mathematics and reached a solution. Thus, students had experience with both traditional and systems approaches to problem solving, and their responses sometimes differed. For example, they sometimes succeeded in traditional problem solving with quadratic equations, but attached less concrete meaning to the mathematical solution than they did to a solution reached through work on a system model.

War and Revolution Seminar

The War and Revolution class provided a unique approach and structure to modeling and the examination of historical events. The course was conceived as a means of applying modeling to an understanding of political-social events. The class functioned much like a college seminar. Through class discussions and independent research projects, students analyzed dynamic political situations from the perspective of decision makers. The intent was to develop both analytical skills and an appreciation of the complexities and importance of policy decisions. Through the course students developed abilities to pose questions, gather relevant information from a variety of sources, develop scenarios depicting relationships among key forces, and critique as well as defend their views.

The teacher used various revolutions to introduce students to systems thinking as a strategy for analyzing the dynamics of historical and current events. They studied basic concepts for modeling systems, reviewed some existing models, and experimented with constructing models of their own. The students prepared final versions of their models of revolution during the last quarter of the year. Each student prepared a systems model to illustrate the dynamic factors underlying their particular topic, presented a formal report and *STELLA* model, and made a presentation to the class describing the model. In addition to normal class work, a special project was conducted in the seminar. Students were asked to model the Zimbardo Prison Experiment and draw parallels to the course's material.

Students' classroom projects included such topics as the 1956 Hungarian Revolution, the Iranian Revolution, and the U.S. Civil War. Each of the students prepared complex causal loop diagrams of their revolution and provided written documentation of the history, theory, and logic on which the models were based. They then prepared structural models that could be run dynamically with *STELLA*. The documentation also included a series of models that illustrated the development of the students' thinking about their projects. Through these projects, students displayed an impressive understanding of the factors that contributed to the historical phenomena: they could identify critical variables and hypothesize the relationships among the variables; these hypothetical interactions were modeled with *STELLA* in an iterative manner — that is, students tested several versions of their model, posing different sets of parameters and examining how changes among those parameters affected outcomes.

The iterative nature of the enterprise helped students to develop their thinking and their models. The process required them to focus on the systemic nature of the problem. To understand the historical phenomena, they could not look at only one isolated incident. Instead, they had to approach the problem by examining the interconnections among a number of variables. Thus, students were forced to ask questions they might otherwise not have considered, to define and redefine their questions, and to focus on the system as a whole. They viewed the systems approach as a technique to help them analyze the problem, structure their thinking, and specify more clearly the historical phenomena.

The systems approach also became a tool for comparative analysis. Students were able to identify similarities among their projects, which enabled them to compare and analyze other phenomena systematically and critically. The generalizability of analysis skills was observed as students consulted among themselves on their individual projects and as they analyzed the Zimbardo Prison Experiment. Although the topic of the special project was somewhat removed from the theme of the seminar, students were immediately aware of the similarities between the experiment and other topics they were studying. More specifically, students recognized that many of the variables and interactions with the

Zimbardo Prison Experiment were similar to their revolutions or other historical events. for exampl , one student noted the similarities between the experiment and the Iranian hostage situation. Another student drew parallels between the experiment and another total institution, the mental institution in *One Flew Over the Cuckoo's Nest*. They were able to use the observed parallels in their analyses of the experiment. More importantly, however, the students were able to apply the analytic and critical problem-solving techniques engendered in systems thinking as they approached the Zimbardo project.

One problem was observed as students prepared models of their class projects and the Zimbardo Experimen Some unsystematic testing occurred when students needed to assign merical values to qualitative phenomena in order to run their *STELLA* models. Although the interrelationships among the variables were specified in their causal loop diagrams and they understood how to quantify numerically-oriented variables, students had some difficulty with the less quantifiable parameters. As one student noted, "people were too hung up on just trying to get a desired graph of their situation, and not trying to see what happened if after they got the graph they changed some things around." Another student presented a slightly different perspective. "Overall, I think that system dynamics is a very good learning tool. Still, I sometimes have to question the validity of assigning values and equations to valueless concepts and unequationable events. But I think that if the conclusions reached from system dynamics are not taken too seriously, the process of creating a model can ultimately benefit the modeler immensely."

Organizational Case Study

The organizational impact of the introduction and implementation of systems thinking was examined at BUHS. The objective was to analyze changes that occurred in the structure and operation of the educational organization as a result of the curriculum innovation and to understand the characteristics of the school, as an organization, that facilitated or prevented the innovation from developing. At BUHS, the idea of introducing systems thinking into the curriculum was established before ETC and ETS became involved. This implied a foundation of administrative support, openness to innovation, and teacher commitment, that probably increased the effectiveness and impact of the innovation.

The organizational case study was carried out using two data collection procedures. The first entailed repeated interviews with the teachers using systems thinking as well as with other teachers and administrators. Interviews were conducted with the superintendent of the district and school board members. These interviews covered such topics as the history of the science education activities at the school, the nature and extent of individuals' involvement, and the perceived changes in the structure and operation of the school that related to systems ctivities. Interviews were repeated to determine if the perceptions of respondents changed over time. Particular attention was paid to real or perceived sources of support or opposition to the project. The second method employed in the case study was classroom observation of systems and content classes. The emphasis in these observations was not on the course content but on the patterns of interaction among students and teachers.

The interviews and observations suggested that the introduction of the systems thinking innovation altered communication patterns among teachers, across departments, and between teachers and administrators. The enthusiasm for the project as it was implemented in the sciences sparked change in other quarters. When English teachers saw their students writing about the systems thinking activities in their science classes, the English Department set about seeking funding for its own computer laboratory.

Overall Conclusions and Implications

The students involved in this project were able to acquire knowledge of systems thinking concepts and apply them to scientific problems at varying levels of complexity and sophistication. Furthermore, modeling activities were integrated in the curriculum in a variety of ways, with different levels of cognitive outcomes. Because of the ongoing nature of the curriculum development, the researchers are unable to make definitive statements about the impact of the systems thinking approach on the acquisition of content-specific knowledge. A more thorough implementation of the curriculum continues to be examined.

Significant developments were observed at BUHS as a result of the curriculum innovation. Many of the changes affect the teachers, the curriculum, and the school as an organization. The infusion of the systems thinking approach into the science classes and the War and Revolution seminar has changed many of the teachers' instructional strategies and procedures for presenting traditional concepts. Given the ongoing nature of the curriculum development effort, it is likely that changes will continue to occur as teachers revise and implement their curriculum modules.

The results indicate that the use of the technology of the Macintosh computer and the *STELLA* software package make accessible to students the modeling capabilities heretofore found only on powerful mainframe computers. Such modeling broadens the range of cognitive representations students can bring to bear in solving problems. The systems thinking approach, in conjunction with the Macintosh's graphics and mouse technology and the *STELLA* environment, allows students to develop and test dynamic models of systems by using a variety of abstract representations to explore and make concrete many phenomena. It appears that the integration of this learning environment into existing curricula has the potential to produce students who have a greater capacity to understand the interrelated and complex nature of many of the phenomena, problems, and events that they encounter in daily life.

The STACI Project serves as a model for implementing a technologically-based curriculum innovation in classroom settings. The systems approach is a flexible perspective that can be readily integrated into a variety of learning environments and content areas. The approach can be taught as adjunct material within a course to supplement existing content. A course can be structured entirely around the theory and concepts engendered in system dynamics. A thinking skills course can use the systems approach as its fundamental approach to general problem solving skills. It also permits teachers to create flexible learning environments. Given a variety of topics within a course, teachers can structure the systems modules as: (a) whole-class activities, using a computer projection system; (b) activities for small working groups; or (c) individual learning experiences. The study of systems thinking in education also enables researchers to examine cognitive, curricular, and organizational questions that might inform policy decisions about other technology-based projects.

RESEARCH IN NEW TECHNOLOGIES

OVERVIEW

The work of the Videodisc and Computer-based Conferencing Projects this year has been characterized by reflection and synthesis. Each of these groups has devoted itself to digesting its work in previous years and examining the relationship of its work to that of others doing similar research. Each has created a framework to help educators evaluate the match between the features of these technologies and the needs and opportunities of particular educational settings.

COMPUTER-BASED CONFERENCING

Eileen McSwiney, Education Collaborative for Greater Boston, Project Leader
Chris Hancock, Technical Education Research Centers
Moira Inghilleri, ETC
Dennis Sayers, ETC
Kathryn Stroud, ETC
Judah L. Schwartz, ETC/Massachusetts Institute of Technology
Thomas Vaughn, Arlington High School, Arlington, Massachusetts
Mary Maxwell (Katz) West, ETC

This project explores the potential of microcomputer-based conferencing as a means for collegial exchange among teachers and between teachers and others, such as scientists and mathematicians, outside the school. The unique capabilities of the medium of asynchronous computer-based conferencing are that participants can read and write messages at whatever time is convenient for them, that groups can interact even though participants are geographically separated, and that messages are available to readers almost instantly. Because the medium had served for over a decade in mainframe computing to support a sense of professional community among geographically dispersed groups in business and academia, it was natural for ETC to consider whether computer conferencing could help solve a well-documented problem among secondary science teachers, namely, their isolation both from ongoing developments in science and science teaching and from colleagues with whom they might exchange ideas about the teaching of science. The Computer-based Conferencing Project's initial conception of conferencing for teachers included both "information sharing" and "discussion." Through the latter, the group hoped that conferencing could be a vehicle for staff development, to revitalize as well as inform teachers' practice through engagement with other teachers and scientists.

The group established the Science Teachers' Network in December 1985 to learn how teachers would use a conferencing system that was designed and managed to facilitate discussion. ETC designed new conferencing software that could run on a microcomputer (so that any educational group in the future could run a conference without an expensive computer), would be easy to use, and would facilitate discussion. Seventy-five science teachers from eastern Massachusetts volunteered to enroll in the network with a number of guests and facilitators. The network was advised by five science supervisors and managed by an experienced staff developer, a graduate student in educational technology, and four teacher moderators. The first year's research, described further below, found that the system was easy to use, that teachers valued the network, and that several factors influenced teachers' use (see also Katz, McSwiney & Stroud, 1987). In order to explore whether increased experience in network use might change the nature of use, the Science Teachers' Network was extended for a second year. In addition, in order to explore whether a network could facilitate communication among teachers engaged in a common task, a second network was established to serve the participants in the ETC Laboratory Site Project, who were using ETC-developed teaching materials in five local schools beginning in September 1986. This group included 38 teachers, teacher/advisors, school support liaisons, and researchers. Because they attended monthly meetings, these network participants had more face-to-face contact that the Science Teachers' Network members had, and they received hands-on training in the system in a preliminary meeting and school visits.

The nature and extent of members' interactions were assessed at three levels — for the conference as a whole, for each teacher, and for messages and message chains. The host computer was programmed to keep a log of all reading and writing actions. Therefore it was possible to know what messages teachers read, as well as what they wrote. In order not to violate the privacy of private mail, the machine did not record the content of these messages, only who wrote to whom, and when.

Influences on participation were expected to fall into two main categories — logistical and social — so both implementation and research activities focused on these areas. Data were collected on members' previous computer experience, location of their computer, phone costs, and other factors affecting the ease of use of the technology. In the social area, network management efforts included facilitation and monitoring of social aspects of network use. In keeping with recommendations made by others (e.g., Feenberg, 1985) attention was given to social facilitation. For example, network moderators welcomed newcomers with personal messages, introduced them to others, reiterated network inquiries that went unanswered, and held two in-person get-togethers. Data collection focused on developing an understanding of teachers' professional social lives and of their work as a whole. Teachers were asked what they considered the main difficulties they faced in science teaching (only 10 percent mentioned "isolation") and how often they met with other science teachers both inside and outside of school. A questionnaire assessed the extent of their previous acquaintanceship with every other member, as well as their perception of members and guests as "experts."

Results

Similar Expectations, Variable Use

When asked how the network had served or not served their interest, teachers most frequently mentioned "keeping in touch" with colleagues and obtaining specific information. Each of these themes was mentioned by about half of network participants.

While 90 percent of the members reported that the network was a very valuable resource, actual use varied widely. About 60 percent continued use, and of these, a quarter were very active users (logging in two or more times per week). Half of continuing users logged in an average of once or more a week. Similarly, a quarter of continuing users were active writers, sending one or more messages a week. Most teachers read about ten times as many messages as they wrote. Some teachers were mainly "readers," continuing to read forums but sending few messages.

The Role of Topic

The potential of the network to provide exchanges on topics of interest among mainly unacquainted persons was demonstrated: 40 percent of messages were public, and of these, half were responses to inquiries or comments on earlier points. Furthermore, common interests clearly brought unacquainted persons into interaction: the majority of teachers wrote to as many previously unknown persons as known persons, clearly following topical interests, not just acquaintanceship.

Two unexpected characteristics of the network messages emerged — their specificity, and their ambiguity. Most exchanges concerned very specific points with discussion of more general topics emerging less often. This continued over the two years of the Science Teachers' Network and thus was not merely a characteristic of new users. Furthermore, the concepts of network use that teachers offered spontaneously in interviews confirmed an interest in specific information.

Some examples are shown below.

Sample Messages
Science Teachers' Network

---

msg no. 1604 filed 11:40 AM Feb 10, 1986
from rose
to nb
re: Photography Course
At Taunton High we are planning to offer a photography course through the science department to average and below average juniors and seniors. Can anyone recommend a suitable book for student use in such a program? Thanks in advance for your suggestions!

---

msg no. 1284 filed 4:49 PM Jan 14, 1986
from charlie

to chemis
re: TESTING EFFICIENCY OF CHEM FUME HOOD
Today I was psyched up to test my hood with some "smoke balls"--made in Taiwan (35 cents), however this was vetoed by higher authorities. Is there any suggestion for other methods of testing out fume hood?
/CHARLIE

---

msg no. 1525 filed 2:19 PM Feb 6, 1986
from helen
to bruce physics chemis
re: IR radiation
A further comment - about why objects at room temperature do not emit visible light: At room temperature the energy of motion of a typical atom or molecule will be of the order of magnitude kT. This applies to any kind of motion; vibrational, translational, rotational, etc - as we learned in thermodynamics, there is 1/2 kT for every degree of freedom. The value of kT at room temperature (300 K) is about 4 x 10^-23 J. A transition of this energy will produce a photon whose wavelength is about 5 x 10^-5 m (using lambda = h c / E), a typical wavelength for infrared radiation. Visible photons have wavelengths about 100 times greater (yellow light = 500nm), or energies 100 times greater. There is no visible light in the spectrum of heat radiation form abjects at room temperature because there is no sizable population of states at the right (i.e. high enough) energies.=

The network was a successful vehicle for exchange of information on specific topics such as these. For example, the last message was a reply to the question:

> How is it that thermal energy is converted to infrared radiation? What I need is a good atomic level explanation! How about it? Any ideas?

In a week this teacher received five replies from four other teachers.

The group also noted that discussions developed around ambiguities in message content. Perhaps because there is no quick way to clarify meanings in this medium, as there is in live conversation, the ambiguities that naturally occurred in the written messages were the basis for participants to chime in with various interpretations. For example, this message

> I am having increasing difficulty getting large enough static charges by rubbing a plastic rod with silk. Any suggestions?

received seven replies, which developed two aspects of the question: (1) *why* the static didn't develop; and (2) what other ways teachers can demonstrate static.

Information Exchange vs. "Discussion"

Teachers' concepts of the network, as well as their actual messages, suggest an information-sharing orientation from which discussions occasionally emerged. On the Science Teachers' Network, facts and experiences were shared, opinions were expressed, and a few heated arguments developed, some about pedagogy. Whether these affected participants deeply enough to change their opinions or to constitute significant professional revitalization is hard to say. There is no direct evidence of this in the discussions, nor did teachers mention deep changes in interviews. Most messages were inquiries and replies on rather specific points. The Lab Site Network was equally used (the average number of messages written per member was the same as in the Science Teachers' Network), but there was very little public discussion. Instead, members wrote messages in private mail, especially from teachers to their advisers. From interviews the group learned that these messages were mainly inquiries on practical aspects of the teachers' work.

One forum in the Science Teachers' Network suggests by comparison with the others that information-sharing may be a safe interaction strategy for unacquainted professionals. This forum differed greatly from others in both social basis and message content. This forum was begun by a few teachers who had trained together at the Harvard Graduate School of Education the year before and wanted to keep in touch. Their strong social motivation was evident in their messages, which contained greetings, reports of contact with other group members, and offers of help and sympathy. These teachers offered topics of a personal nature, reflected in topic lines: "emotions," "feedback," "reflections." Message sequences followed a single evolving topic rather than several unrelated topics. A new network started this year at Harvard for teachers in that program has been heavily used — 1500 calls in two months. These teachers share their experiences in graduate school together and their transition to new jobs around the country — more powerful common experiences than the other members of the Science Teachers' Network.

The greater acquaintanceship and involvement in a common task of the lab site participants did not, however, result in more public discussion than occurred among the science teachers; on the contrary, only 15 percent of lab site messages were public, compared with about 40 percent in both years among the science teachers. Lab site teachers also shared experiences at their monthly group meetings, and some said they found it "hard to banter" on the network. The average number of messages written per member was about equal in the two networks, as was the total number of messages, but use differed. The lab site use was weighted toward private communication between the new and more experienced teachers.

Implications for Network Design and Management

Adding these observations to those of other network researchers suggests that network managers consider the motivation for participation, deriving from both the social conditions and task conditions present in a network group. The ETC networks and other collegial exchange networks have found wide variation among members in frequency of network use. Managers of collegial exchange networks based on common interests but no common tasks should not expect all members to participate. Perhaps 100 percent participation should be expected only if the group pursues a joint task requiring their collaboration and one which cannot be accomplished without the network communications. With the present state of the technology, common interest networks do not appear to provide convenient enough communication to entice all members into interactions not essential to their work. Nevertheless, there is enthusiastic use by some. The Computer-based Conferencing Group suggests that network communications might follow the same model that one would expect to predict level of communication in face-to-face activities, as below:

Task Basis for Communication		*Social Basis for Communication*: Unacquainted	*Social Basis for Communication*: Acquainted
	Common Task	High	High
	No Task (*common interest only*)	Low	High

TABLE 1. Level of Network Participation Expected Under Different Task and Social Conditions.

Both social and task dimensions are roughly continuous variables. Either social motivation or task demands seem to elicit communications; where both are low or unstructured, the lowest amount of communication is predicted, measured either as percent of the group who participate, or level of participation by individuals.

Among unacquainted teachers the topic of talk seems to be a very significant influence on participation, gaining salience and leverage in the interaction process. This, in itself, is not surprising, given that participants are unacquainted, invisible to each other, and must rely on written messages in order to interact. There are, however, two particular features of how topics appear that have implications for choice of application and method of management of computer-based conferences: (1) the reliance on specific topics among unacquainted members; and (2) the potential for ambiguity in topic development. Unacquainted people interacting through writing on a computer network may resort to specific topics in order to compensate for the lack of ability to rapidly clarify meanings as they do in face-to-face exchanges. Since rapid clarification of meanings is impossible, ambiguities remain in a message, and a topic can be developed along multiple threads (Black et al., 1983).

Each of these features has practical consequences for collegial exchange. If unacquainted members need to communicate about specific information, network design must build in the critical mass of expertise and interest needed for interactions to be sustained.

The more specific and varied members' interests, the larger the membership should be. In planning a collegial exchange network, managers should estimate whether there is enough interest on core issues and whether these issues can be discussed effectively in written exchange and with variable response time. For a collegial exchange network of mostly unacquainted members to succeed, where members have common interests but no common task to structure interactions, a large membership is recommended to meet the specific, possibly diverse, interests of members. For ETC's Science Teachers' Network, more than 75 members might have been beneficial; given the rate of use, perhaps 200 enrollees (or 100 active users) would have been ideal. Guest experts provide additional knowledge resources but must be chosen to match members' interests. The large membership approach maximizes the information sharing potential within the group, which may be a prerequisite for discussion to emerge among unacquainted persons.

Choosing Tasks

For task-oriented networks such as the Lab Site Network, planners should consider the fundamental communication needs of the task and whether they are compatible with features of the medium — whether variable and uncertain response time will benefit or hinder the task, whether the tasks can be carried out effectively through written exchanges without the opportunity for rapid clarification of meanings, and whether the task can benefit from diverse interpretations and wide group access as the medium allows. As others have suggested (Black et al., 1983; Waugh et al., 1988), tasks needing diverse interpretations, through expansive and perhaps even playful interactions, might thrive in this medium. Sociological research comparing group problem solving in face-to-face groups with that by computer conferencing also supports this view (Kerr & Hiltz, 1982).

Capitalizing on Ambiguity

The constructive use of ambiguity in message content, an ambiguity sustained by the medium's asynchronicity, may facilitate the expression and integration of different points of view into a discussion. Research on a variety of tasks and in a variety of settings in which face-to-face interactions are compared with computer-mediated interactions concurs that there is unusual opportunity in this medium for multiple points of view to be expressed and integrated (Kerr & Hiltz, 1982; Black et al., 1983; Levin, Kim & Reil, 1988; Waugh et al., 1988).

Face to face interactions may allow ambiguities to be quickly resolved, but the lack of opportunity to do so in asynchronous electronic interactions is not necessarily a weakness of the medium. Human beings are expert at negotiating ambiguity constructively. Our ways of negotiating social interactions in daily life (e.g. Goffman, 1974), as well as our enjoyment of literature, drama and poetry, are built upon our ability to interpret and delight in verbal ambiguity. How written electronic interactions can best build upon this quality needs to be explored by examining the development and success of different kinds of network tasks and topics. Analyses of this kind are being made by Levin and Miyake (see Waugh et al., 1988).

VIDEODISC

Kim Storey, WGBH Educational Foundation, Project Leader
Karen Janszen, WGBH Educational Foundation
Carolyn Mellin, WGBH Educational Foundation
Anne Favaloro, WGBH Educational Foundation

Like television and microcomputers before it, videodisc has been heralded as a revolutionary educational technology — one that combines the best features of other media. While some industry observers liken videodisc to Gutenberg's printing press as a milestone in information technology, educational researchers and practitioners see it primarily as a visual medium with great promise for instructional use. Certainly, videodisc's ability to store and randc ıly retrieve vast amounts of high-quality visual data present intriguing new teaching and learning opportunities.

With the adoption of videodisc and even newer multimedia technology (e ;., Digital Video Interactive — DVI) still two to five years away in mainstream schools, the Videodisc Research Group took the opportunity to step back and assess what these new media might mean for teachers and learners. The group investigated a variety of aspects of educational videodisc, first studying the process of videodisc creation by designing and producing an interactive videodisc from existing video materials using an authoring system, then studying the use of the prototype videodisc in middle school science classrooms, and finally preparing an analytic paper on the influences of videodisc design and school factors on videodisc use in classrooms.

The Design of a Prototype InteractiveVideodisc

Two general principles guided the Group's early thoughts about the research videodisc. First, researchers wanted the disc to serve as a tool for investigating the effectiveness of videodisc for presenting a discovery approach to science. Second, they wanted to study the process of videodisc creation. Recognizing that retrofitting existing video through the use of an authoring system could be a quick and cost-effective means of developing educational videodisc applications, the group decided to create the research videodisc by this process. The experience of designing the videodisc revealed the opportunities and constraints of creating retrofitted videodiscs.

The research videodisc, *Seeing the Unseen*, was created using existing video segments from NOVA and 3-2-1 CONTACT and an authoring system, Authority (TM), developed by Interactive Training Systems, Inc. Rather than simply presenting scientific information,*Seeing the Unseen* employs an inquiry approach to science education in which students explore and inquire as scientists do. The disc provides an environment or microworld in which students can carry out investigations.

Students hone various techniques associated with scientific explorations through interactions with four lessons. These techniques include: making observations; collecting, recording, and classifying data; seeking patterns; forming and refining hypotheses; conducting experiments; and making predictions. The techniques are not practiced independently from each other and are not viewed as separate or linear steps in a problem solving process. Some, but not all, of these techniques are required for each lesson.

Each of the four lessons focuses on a different problem posed as a question. While the lessons present topical information (plants and light, animal camouflage and mimicry, time and motion, and the geometry of shapes), the value of each lesson is derived from using a variety of techniques of scientific exploration to examine the subject matter. The problem-solving methods required vary from lesson to lesson depending on the teaching strategy employed and the mode of inquiry elicited.

The four lessons take advantage of the many forms of interactivity available with videodisc technology. Computer control of the videodisc permits branching based on students' responses, use of two audio channels, random access to visuals and automatic search, and the presentation of text screens as well as text and graphic overlays. Specific interactive options built into the lessons include video pause (freeze-frame), video replay (forward or backward), redo (return to an earlier activity, menu (go back to the last menu), and go ahead (go to next menu, screen, or activity). In some lessons, students can also choose to view charts, lists of thought questions, or additional information. The user controls the system primarily by touching the screen, although keyboard input is required in some instances.

The first stage of videodisc research focused on the question: What are the design choices and compromises regarding video resources, authoring system, and instructional strategies when existing science television programs are retrofitted to create videodisc using an authoring system?

The group identified a trade-off: retrofitting and use of an authoring system saved time and money, but the videodisc lessons had to be developed within established parameters. Design work could not progress from an ideal concept to a concrete realization. Instead, the group started with the concrete — visual images from science television programs — and fashioned these images into lessons in the best ways offered by the authoring system, consistent with the group's instructional strategies and videodisc theme.

Because the kinds of visuals that take advantage of videodisc's capabilities are not readily available from conventional video resources, including NOVA and 3-2-1 CONTACT, which are designed for linear viewing, this method of videodisc creation limited the use of video segments mostly to visual databases for illustrating content. Lacking a high degree of visual and manipulative appeal in particular, the available video images precluded instructional strategies that use visuals for simulations and new applications unique to the videodisc medium.

The group found that the content or subject of the video images affects the retrofitting process as much as the nature of the video images. Existing video already has visual subjects and content, carefully taped and edited to suit a narrow purpose. Although new narration can be written, use of existing video requires acceptance of established visual images. Rarely can these images be made to fit another use in the same or a different medium. With visual images predetermined in subject and scope, retrofitted videodiscs are perhaps more appropriate for teaching skills than for teaching specific subject matter.

The design and development process for the research videodisc began with, and repeatedly returned to, the video resources. The group's experience with the process of retrofitting led it to conclude that the overriding influence of video resources is a serious design concern for the creation of retrofitted videodiscs, regardless of subject area, instructional approach, or means of programming. However, the group recognized that designing and then programming the research videodisc from scratch might have proved equally difficult, but for different reasons. Both means of disc creation present disc designers with challenges.

Although the process of retrofitting was arduous, intensive designing and redesigning assured that existing visuals were integrated with computer-generated interactions in ways that met the design objectives. The group created the research videodisc especially for use with middle school science students. In addition, the disc was a design sampler, with four lessons that illustrate a variety of videodisc presentations and interactions. The next phase of the research explored the use of this disc with middle school students and teachers.

A Prototype Science Interactive Videodisc: Research on In-school Use

The Videodisc Group used the research videodisc, *Seeing the Unseen*, to explore five aspects of videodisc technology: (1) the importance of user control and interactivity; (2) the importance of high quality visuals; (3) the potential of videodisc for promoting inquiry learning; (4) the effectiveness of individual, small group, and whole-class instruction; and (5) the teacher's role in using videodisc technology.

Of 116 middle and junior high school students in the study, 86 participated in whole-class sessions, 12 used the disc individually, and 18 used it in pairs. Researchers observed students as they proceeded through the lessons, noting their strategies and their difficulties, as well as their interactions with each other and with their teacher. Interviews and questionnaires elicited student reactions to the technology and informally assessed their grasp of the concepts and skills presented. Interviews probed the teachers' perceptions of the lessons and of the classroom implications of the technology.

The interactive and visual nature of the medium proved to be the most salient and appreciated aspect of the technology. Students and teachers alike defined the technology (based on experience only with this particular disc) as both participatory and illustrative. For students, these features set videodisc technology apart from other educational media and teaching techniques (e.g., books, television, computers, classroom lecture and discussion) and led them to conclude that videodiscs foster more effective and engaging learning experiences. Students repeatedly credited the visuals as making videodisc use interesting and fun.

Knowledge of the conventions of television shows, computer software, and even video games (e.g., documentary narration, menus, varying levels of difficulty) may also have given students the know-how and confidence to approach the videodisc system without apprehension and to adapt to it quickly. While no student had played a videodisc before, nearly all were able to use the system readily and quickly solve problems with disc operation without the assistance of an observer.

The ways students took advantage of the medium, including their use of various options, and their post-use level of comprehension, indicate that a microenvironment designed to promote inquiry learning of science information and concepts can be successfully created on videodiscs. Indeed, compelling visual images, interactivity, and an exploratory approach proved to be a powerful combination which captured and retained the interest of students. Students working alone or in pairs enjoyed actively working out problems because they could control the order and pace of information presented and gain access to material as desired. Once involved, these students never gave up on a problem, and if they had not completed an activity by the end of a 45-minute session, they wanted to continue.

Given their recognition of the advantages of interactivity and high quality visuals, it is not surprising that most students said they would prefer not to use the disc in a classroom. Whole class groups restricted personal involvement — too many students demanded varying options, the teacher usually determined direction and path, and the screen was too small for everyone to view the video images and read text. Those students who were able to maintain a high degree of involvement were forced into a competitive mode in which they had to shout out their answers, opinions, and requests, many of which were not addressed.

Students did, however, consider the social context of disc use to be very important. While most recognized the problems inherent in large-group use, they also said they would prefer not to use the disc alone. They regarded pairs or small groups as the best use mode. Apparently students felt that in pairs and small groups they could exploit a wide range of videodisc characteristics, particularly control and participation, while benefiting from the manageable and interesting input of just one or two other people. Interestingly, female students showed a greater appreciation for the benefits of pair and small-group use than boys. It may be that girls generally prefer a more social and intimate learning situation.

It must be noted that many students said they preferred the mode of use they had experienced as part of the study. The fact that students in each mode reported enriching experiences suggests that the technology can be used successfully in a variety of settings.

The design of *Seeing the Unseen* may also have influenced students' use mode preferences. As a design sampler intended to foster discovery learning through various forms of interaction, the disc activities are more effectively accomplished by small groups of learners and are less suited to large-group use. Indeed, the research group hypothesized that specific videodisc designs may be more appropriate to certain use modes: whereas, an inquiry-oriented disc works well for small groups of learners working independently, an archival disc might prove best for whole classes working under the direction of a teacher. The group explored these issues in the next research phase.

Another issue the group continued to research is the role teachers play when videodiscs are used in schools. Students' acceptance and appreciation of the control afforded them by the videodisc suggests that teachers should provide opportunities for exploiting this advantage, either directly or indirectly.

When discs are used by pairs or small groups, sometimes outside the classroom, the teacher's role is almost always indirect. Teachers usually introduce and follow-up on the activity by providing a curricular context, a role analogous to that fostered by computer use in a lab. The teacher's role in the classroom is more uncertain. While teachers in the study recognized that their most effective role might be as guide rather than director, several had difficulty assuming that role. Some allowed students to interact freely with the disc; others took complete control of disc operation. None of the teachers fully exploited the disc's inquiry approach.

Making the most of the teacher's role may lie both in designing discs to suit existing teaching styles and settings, and in teaching teachers how to take advantage of the new technology. Explaining to teachers the potentials and constraints of the medium and reviewing the content of an individual disc could lead to more effective uses of the technology. Experimental lesson plans, which show teachers how to incorporate specific videodiscs into existing curricula, might be developed and tested. In addition, examining teaching models that work with other educational technologies might suggest new ways to use videodiscs in the classroom.

In conclusion, this phase of the Videodisc Group's research supports the promise of videodisc technology for educational use. The medium appears to provide students with unrealized opportunities for taking control of their own learning in an educational experience that is interesting, social, and fun. The significance of the technology to classroom teachers is less clear. In the third and last phase of the ETC videodisc research, the group explored the place of videodiscs in the nation's classrooms.

Educational Videodiscs: The Influence of Design Approaches and School Factors on Early Classroom Uses

Although the group's research in schools using *Seeing the Unseen* showed that students and teachers were enthusiastic about the videodisc, especially its compelling visual images and interactivity, researchers realized that the disc's structured design approach limited users' ability to control the learning experience. Students working individually or in pairs found they could choose different options and control the pace of their interactions, but their movement through disc content was mostly linear and predetermined by built-in instructional designs. Among classroom groups, the videodisc served largely as a presentation tool managed by the teacher, further restricting individual interactions and control.

These findings led the group to ask how different videodisc design approaches influence teaching and learning and how school factors influence videodisc use. The team began to wonder what will happen when videodisc technology becomes more widely available and teachers begin experimenting with it in their classrooms. What factors will influence how teachers and students use videodisc technology? How can teachers and students most effectively use videodisc in the classroom?

To answer these questions the group undertook a review of the existing literature on videodisc technology and educational design approaches and investigated several examples of early experimental use of videodisc in schools. The resulting paper discusses how videodisc design, in combination with school factors, such as teaching and learning activities, access to equipment, and school culture, affect how videodisc is used in classrooms. The paper illustrates its points with several case studies and, finally, suggests ways for secondary school teachers to take best advantage of what is uniquely useful about the technology.

Rather than furthering the status quo, the Videodisc Group believes that videodisc can spur innovations in the educational process if its use occurs within the framework of new ideas about teaching with technology. The benefits may be realized on several different levels, from simply improving the quantity and quality of multimedia presentations in classrooms to empowering a student to create an original multimedia work by manipulating materials on an existing disc. (As videotaping and editing equipment is more widely used in schools, students and teachers will also create their own discs.)

Research at ETC has emphasized the importance of using technology in teaching for understanding. This approach encourages analytical reasoning in which students take active roles in exploring problems and their teachers guide them to construct new knowledge and reach new understandings. The Videodisc Group believes that videodisc can promote such understanding through active inquiry by offering opportunities for teachers and students to choose, explore, and manipulate a wealth of visual presentations. The research indicates that these opportunities occur most often when videodiscs are used in three ways.

(1) *Videodisc materials (disc images and related software text and graphics) serve as visual aids and catalysts.* When used by a teacher with an entire classroom of students, selected disc materials are used to present material for exploration, instruction, explanation, and discussion.

(2) *Videodisc materials serve as raw data for study.* Individuals and small groups of students investigate disc materials during periods of independent study in which they explore topics of interest, and find and make connections that are meaningful to them.

(3) *Videodisc materials serve as part of newly created presentations or other kinds of original multimedia constructions.* Using authoring systems, students and teachers create new multimedia works by reorganizing and inventing new purposes for existing materials.

Although many variations exist, these three primary uses take advantage of what videodisc does well, fit the greatest number of anticipated use patterns, and encourage practices that support active roles in teaching and learning. Because of existing traditions, the group believes that in the near future the first use strategy will be primarily employed by teachers, and the second will be primarily employed by students. The third strategy is already used by both students and teachers.

Designing for the Future

The three suggested uses outline a general design framework for school-based videodiscs. Disc designs must support three purposes: presentational medium for teachers (and students); research resource for students (and teachers); and multimedia construction maker for both teachers and students. The first two functions can be seen as two ends of a continuum with authoring and editing capabilities mediating both and enabling the creation of multimedia works (some presentational in nature, others more for research and other uses) by teachers and students.

In general, the types of disc designs that are most amenable to the suggested uses and purposes offer flexibility in content and adaptability in format. In other words, subject matter is presented on many levels with the potential for nearly endless interconnections and a nearly infinite number of user determined paths of exploration. Format is structured enough to enable users to identify organizing principles and thus navigate through or manipulate materials, but not so structured as to control the pace and path of interactions. Databases, for example, provide visual material in bite-sized pieces that can be readily manipulated to serve a variety of purposes in a range of settings.

The research shows, however, that videodiscs designed for classroom use might balance open-ended design approaches with one or more structured approaches (e.g., storytelling) so that teachers' needs are met. Teachers often do not have adequate time or access to equipment to prepare original organizations of disc materials to support their lectures, and they often have their students use videodisc in small groups while the rest of the class is involved in another activity.

These conditions suggest that embedding a few packaged presentations — for use by teachers during whole-class lessons or by students working independently — will make discs more useful in many classrooms. Such presentations need not be more than sample routes through the images that serve as introductions to the subject matter, perhaps guided by a thematic question or a specific problem. The presentations will also serve as models of what teachers and students can create on their own, given sufficient time and access. Thus, the core of a model disc design might be a database, but some instructional activities using the database might also be prepackaged.

In addition to a disc and its related software, educational disc products should come with printed user support information. This information, teachers report, should include an index of all images, an outline of software content, sample lesson plans, activity sheets, and possible lecture scripts. These materials would instill confidence and provide guidance on how to teach with the technology, particularly for those teachers who lack school-wide support or peers with whom to share experiences.

New hardware configurations will also make using videodiscs easier and support the kinds of use strategies the group recommends. For many teachers, logistical factors make videodisc impractical — they need advice on how to make the most of limited resources. Simplified hookups between players, computers, and monitors are required. Large screen monitors and easy-to-use keypad control devices are also needed. Equipment that must be shared should be made mobile by placing it on a cart.

The most promising disc designs will allow teachers to retain two critical roles, guiding learning and assessing student performance. They will also encourage students to become knowledge detectives — users who actively pursue information and its meanings. Creative and well-informed designs will enable teachers and students to maintain active and constructive roles in the teaching and learning process while exploiting the most interesting and creative potentials of the technology.

RESEARCH IN LABORATORY SITES

Martha Stone Wiske, ETC, Project Leader
Daniel Chazan, Education Development Center
Ava Davidson, Newton North High School, Newton, Massachusetts
Joellen Hillyer, Newton North High School, Newton, Massachusetts
Richard Houde, Weston High School, Weston, Massachusetts
Magdalene Lampert, Michigan State University
David Niguidula, ETC
Patricia Orzulak, Ware High School, Ware, Massachusetts
Mary Sapienza, Newton North High School, Newton, Massachusetts
Gary Simon, Cambridge Rindge and Latin School, Cambridge, Massachusetts
Joy Shepard, ETC

The Educational Technology Center has always been committed to conducting educational research that leads to improved instruction in schools. That commitment implies an integrated approach combining research into learning problems with development and analysis of new instructional approaches, and continuing attention to issues of practical implementation in regular school settings. By the end of ETC's third year of operation, several of the Center's research groups had produced experimental instructional units ready to be tried out by classroom teachers in a range of secondary schools. Accordingly, in the spring of 1986, ETC established laboratory sites in five Massachusetts high schools.

The laboratory sites were conceived as places where regular classroom teachers would collaborate with members of ETC research and development groups to accomplish two aims:

(1) to demonstrate ETC's technology-enhanced guided inquiry approach to instruction in science, mathematics, and computing,

(2) to learn what it takes--materials, implementation assistance, organizational structures--to make this approach workable in schools.

The Laboratory Site Project — Year 4

During the 1986-87 academic year ETC supported and studied laboratory sites in five secondary schools: a small inner-city school in a large urban school system, a small high school in a rural area, and comprehensive high schools in a small city, a middle-class suburb, and an upper middle-class suburb. The project focused on three ETC-developed innovations: teaching with the *Geometric Supposer*, using Microcomputer-Based Laboratory equipment to teach students about heat and temperature, and infusing the Programming Metacourse into introductory classes in BASIC. Each of the innovations exemplified ETC's approach to using new technologies to support guided inquiry. This approach focuses on engaging students in active investigation of problems with the teacher facilitating students' empirical inquiry and analysis of data to build theories and to solve problems.

The lab site project was designed to take into account lessons from previous efforts to reform teaching practice through the introduction of innovative materials and strategies developed outside the school system. Briefly summarized, these lessons included: focus on the teacher as the primary character in classroom innovation; generate support from administrators, support an on-site facilitator; present a clear vision of the desired teaching approach; follow initial training with continued assistance from an advisor; build networks of innovators; sustain innovation through a community of reflective colleagues (Crandall et al., 1982; Huberman & Miles, 1984).

As much as possible, these principles guided the design and management of the lab site project. In each of the five sites, initial discussions were held with the superintendent and building principal to ensure administrative support. These people identified appropriate personnel to introduce the project to department chairpeople and faculty. At each level, expectations were clarified, and participation was invited not required.

The project attempted to recruit at least two teachers for each of the three innovations at each laboratory site, although this goal was compromised in a few cases where too few teachers taught appropriate courses or chose to volunteer. An on-site liaison was recruited at each site to link the project to the norms and structures of the school and to facilitate effective dialogue between ETC and the lab site participants. Three advisors were hired, one for each subject matter strand. These experienced classroom teachers helped lab site teachers plan lessons, adapt materials, and work out practical teaching strategies. The advisors helped translate research results into practical classroom terms and, with the lab site teachers, met regularly with the ETC researchers to report on their implementation of research-based approaches in the classroom. In effect, the advisors served as analogues of the on-site liaisons by facilitating a dialogue between theory and practice.

Lab site research was based on an interactive model of change, whereby an innovation alters classroom practice while features of the implementation setting and process alter the innovation itself. Our aim was to understand the aspects of the innovations and the lab site settings that necessitated and shaped these mutual adaptations.

The research included two studies. One focused at the school level, yielding case studies of three lab sites. These case studies traced the progress of the three strands of the project, clarifying what promoted and impeded their implementation. The second study focused on the teachers involved in the geometry strand of the project. Its aim was to understand how teachers' knowledge, skills, and beliefs affected their use of the ETC-developed innovations and to clarify the kinds of experiences that enabled teachers to change their ideas and practices. The two studies were expected to illuminate not only the process of implementing ETC-developed innovations, but the more general issues affecting the integration of technology-enhanced guided inquiry into subject matter instruction in secondary schools.

The Laboratory Site Project demonstrated that ETC-developed innovations could be carried out successfully in a range of school and classroom settings, given the kinds of support provided by the project. Focused as it was on the process rather than the impact of implementation, the project revealed features of the innovations and the settings that shaped this process. [See ETC technical reports TR88-1 by Lampert, 1988 and TR88-3 by Wiske, Niguidula, and Shepard for fuller discussion of the project's results during its first year.] Broadly speaking, the implementation requirements can be considered within two general categories: (1) the prerequisite conditions for introducing ETC-developed innovations in schools, and (2) the more subtle conditions shaping the integration of technology-enhanced guided inquiry into classroom curriculum and practice.

Prerequisite Conditions

The prerequisites for integrating new technologies to improve instruction are frequently underestimated, especially by computer enthusiasts. Nevertheless, the Lab Site Project confirmed what veteran computer-users know: gaining access to appropriate hardware, software, and related materials can be major barriers to effective use of educational technology. The complex process of acquiring necessary resources, locating and preparing facilities, and arranging schedules to enable effective access is a logistical challenge requiring coordination across various units within a school. The Lab Site Project reduced these barriers in several ways. Apple Computer, Inc. donated a substantial amount of computer hardware to the project, enabling ETC to supply a computer laboratory at each site. Software was supplied by ETC and by Sunburst, Inc. which published the *Geometric Supposer*. Lab site liaisons and advisors supplied extensive technical assistance, including many hours of setting up equipment and arranging for its maintenance and repair. Teachers acknowledged that the technical expertise and moral support provided by these helpers was crucial in the early stages of acclimating to new technologies.

Integration Challenges

Integration challenges were shaped by the degree to which the innovation differed from existing conditions in the classroom and the school context. The degree of "fit" between prior practice and the innovation was notable in three aspects of classroom life—curriculum, technology, and teaching approach. To the extent that the innovation was congruent with existing practice the implementation was smoother. If, for example, teachers were already familiar with the technology — as was true in the case of the programming innovation — the change was easier than if teachers were adjusting to an entirely new, complicated technology. Similarly, if teachers were accustomed to a guided inquiry approach focused on engaging students in problem solving, the innovation was easier than if their usual instructional method was didactic. Both programming and science teachers were accustomed to engaging their students in inquiry-oriented lab sessions, but geometry teachers were not. In cases where the gap between prior and desired practice was large, surmounting it was easier when the innovation methods and materials were fairly complete. The *Metacourse*, for instance, was highly elaborated with detailed lesson plans, teaching aids, and problems suitable for in-class lessons and homework assignments. The geometry project supplied a large number of problems, but teachers struggled to select and modify them in ways that would fit into their course syllabus. The challenge of inventing and integrating the [illegible] wrapping for the innovation was even greater for the heat/temperature teachers. [illegible] ght a range of secondary science courses and most found the materials developed by the ETC researchers for experimental lessons had to be significantly altered to suit their syllabus and students.

In addition to these aspects of classroom life, organizational features of school systems exerted a powerful influence on the process of carrying out technology-enhanced guided inquiry in lab sites. Individual teachers varied in their curricula and preferred teaching approach, but these personal variations were influenced by goals, norms, and structures of their school contexts. School systems and buildings differed in the goals and self-image they embraced. In one system, academic excellence was a priority; in another the maintenance of a harmonious self-reproducing social community was the dominant goal; in a third the emphasis was on "remediation" of students' academic skills which were perceived to be deficient. The compatablity varied between the dominant district goals and the goals of this innovation which were to improve students' understanding of subject matter by engaging them in active inquiry.

The structures and values which shaped teachers' conceptions of their roles were another powerful school-wide influence. For most teachers, the integration of a guided inquiry approach constituted a significant shift from a teacher-centered mode in which they transmitted knowledge to their students toward a more student-centered mode in which students constructed their own knowledge. Some school structures were more compatible with this educational shift than others. For example, in one school teachers of a particular course met as a curriculum team, in consultation with the department chairperson, to design the syllabus of the course and to prepare department-wide exams. This approach to making decisions about curriculum and assessment was mirrored in other school structures and norms which encouraged teachers to view themselves as responsible and capable to exercise professional judgments. This professional context was compatible with a pedagogical approach that required teachers to exercise and share authority for making knowledge in the classroom. In other laboratory sites, school norms and structures tended to be less supportive of teachers as makers and critiquers of knowledge. Key decisions about curriculum and assessment, for instance, might be made either by some central body that limited teachers' autonomy or in a vague way that left teachers uncertain about their rights and responsibilities for exercising professional judgment. Under these circumstances, teachers were less inclined to take and to share the authority for making knowledge in ways that a guided inquiry approach entails.

Fifth Year Research Results

The findings from Year 4 recommended a closer investigation of how teachers manage to integrate guided inquiry into their practice. Such instructional approaches are urgently favored by a varied set of would-be school reformers. Groups as diverse as learning theorists, professional educators, and business leaders urge an instructional approach that teaches deep understanding of core concepts, that develops students' capacity to pose and solve problems and to appreciate the process of making and critiquing knowledge. The experience of lab site teachers illuminated both barriers to these lofty goals and possible paths for reaching them. At the end of the 1986-87 academic year, the geometry teachers in three ETC laboratory sites voiced their desire both to continue teaching with the *Supposer* and to spread the innovation to other colleagues in their schools. Their intentions created an opportunity to conduct a related set of studies affording a more penetrating analysis of the implementation process. The questions these studies addressed were:

(1) How do teachers' concerns evolve as they incorporate technology-enhanced guided inquiry into their practice and what kinds of implementation assistance address these concerns?

(2) How do teachers integrate students' ideas with their own curricular agendas?

(3) How do the structures and values of the school context influence the implementation and spread of this type of educational innovation?

Data were gathered through observations, interviews, and extended action research interventions with geometry teachers in three laboratory sites throughout the 1987-88 academic year. The geometry advisor who worked with the teachers during the first year of the lab site project continued to serve both as an advisor and as a researcher during the second. In this capacity he consulted with teachers about planning lessons and designing teaching materials and tests; he also observed their classes regularly and discussed teaching strategies with them. After each visit he made extensive notes about his observations, which were then analyzed in relation to research on teacher and school change. The study of teachers' strategies for connecting students' ideas with their own agendas made use of the same data, which was supplemented by a series of observations and interviews with teachers focused specifically on how they make these connections. The interviews were transcribed and analyzed in relation to research on alternative epistomologies and sociolinguistic patterns in the classroom. The study of the spread of innovations in relation to school cultures was conducted through an ethnographic study which included document analysis, interviews, and observations. Data were collected not only from the veteran geometry teachers but also from the colleagues to whom they attempted to spread the innovation and from other school personnel and events that provided insights into the school values, routines, and organizational structures.

Teachers' Evolving Concerns

Teachers' evolving concerns during their second year of teaching through guided inquiry with new technologies were analyzed in relation to the Concerns Based Adoption Model (Hall & Loucks, 1978; Hall & Hord, 1987). This framework traces the progression of teachers' concerns as they work with an innovation; it begins with personal concerns and continues through questions about classroom management issues, concerns about consequences, and interest in modifying and extending the innovation. This study, undertaken during teachers' second year with the innovation focused particularly on their questions about management and consequences. [See Wiske & Houde, (in press) for a fuller description of results from this research.]

Management concerns appeared to be a reflection of teachers' struggles to balance attention to multiple agendas. Teachers wished to address several academic content agendas (ignoring for the moment other important agendas such as students' social and emotional development): covering the geometry content and deductive reasoning of the traditional curriculum, teaching students how to reason inductively, and helping them understand how empirically-based inquiry and formal deductive reasoning are integrated in the making of mathematics. In addressing these agendas teachers blended didactic instruction, which for most of them had been their predominant mode for teaching geometry, with the inquiry-oriented problem-focused approach entailed by this innovation. In the context of balancing multiple curricular and pedagogical agendas, teachers' management concerns included a wider range of issues than those normally associated with "classroom management." Management concerns arose at every level of lesson planning from the design of exercises and teaching materials, to the management of classroom interactions, to the sequencing and structure of curricular units and the overall course architecture. At each level teachers faced questions of pedagogical approach and format, combining teacher-led classes with sessions when students worked in pairs in the computer laboratory, integrating in-class work with homework assignments, and connecting the textbook with *Geometric Supposer*-based lessons.

As teachers worked through these challenges of integrating technology-enhanced guided inquiry into their courses, they confronted questions of impact and consequences. Their concerns focused on three issues: time, assessment, and authority. They found that teaching in this way required more time for them to plan, think, and evaluate student work. Students also required more time, in larger chunks than the traditional 45-minute periods, to learn through inquiry. While students might learn better and with more interest through this approach, teachers found themselves facing questions about what to cut from the traditional curriculum in order to leave time for inquiry. Concerns about assessment arose partly because the innovation addressed goals not generally encompassed by the standard geometry assignments and tests administered in schools. Teachers had to find new instruments and new ways of reviewing student work to take into account both the goals of guided inquiry and the fact that students often worked collaboratively on assignments.

The introduction of this innovation shifted the basis for authority in the classroom in pervasive, multifaceted ways. Teachers exercised greater authority for deciding what to teach and how to teach while reducing the textbook and curriculum guide as shapers of these decisions. Students exercised more authority as makers and critiquers of knowledge rather than as passive recipients of knowledge transmitted to them by their teachers or textbooks. Another type of shift stemmed from the design of the *Geometric Supposer* software whose menu structure enabled and invited investigation of certain aspects of geometry which are not generally emphasized in the standard geometry course. By helping students and teachers investigate these geometric ideas, the software challenged the textbook as a guide to the scope and sequence of curricular topics.

In dealing with these wide-ranging concerns teachers needed several kinds of implementation assistance. They needed regular consultation with an experienced advisor who not only offered suggestions but helped them develop and appreciate their own inventions of methods and materials. Exchange with colleagues engaged in a similar innovation was both stimulating and supportive. Time to plan, prepare, think about students' work, and figure out appropriate responses was scarce but essential.

Looking across teachers' efforts to deal with concerns about management and consequences, some persistent curricular and pedagogical dilemmas recur. The curricular dilemmas turn on basic epistomological issues: does one focus on knowledge of content or knowledge of reasoning processes, does one focus on transmitting the accepted "public wisdom" or on helping students to construct their own personal understandings? Related pedagogical dilemmas include: is learning a matter of individual development or the result of social interaction; what is the proper balance of teacher versus student control over the focus, pace, and standards of instruction?

Teachers' reactions to these concerns and dilemmas appeared to reflect their own goals and preferred teaching styles, their assessment of their students' level of academic ability and learning needs, and their school system's prevailing goals and norms. In addition, there was some indication that teachers gradually began to see ways of resolving these dilemmas at least some of the time. By altering the terms of classroom discourse, by modeling inductive inquiry, and by crediting students' ideas, they could educate and reinforce students' inductive reasoning skills without always taking time from other agendas. As described below, they found ways to connect students' ideas with their own agendas, thereby reducing the degree to which they had to choose between the two. While experience might diminish some of the strain of integrating guided inquiry into the classroom, this approach continued to be extremely demanding of teachers' time, skill, and knowledge.

Connecting Students' Ideas with Teachers' Agendas

Assuming guided inquiry as a pedagogical ideal in mathematics education implies that teaching must connect students' thinking about a subject with curricular agendas and instructional goals. Commonly, mathematics is associated with remembering what to do, with "knowing it," with being able to get the right answer quickly. Because students are not typically inclined to consider their active inquiry as a route to acquiring the knowledge that is valued in school, such teaching must simultaneously elicit students' engagement in inquiry and legitimate inquiry as a route to learning. Teachers must accomplish this feat even as the traditional norms of the situation in which they teach work against students taking their own thinking seriously as a route to being successful. Within this conceptual framework, the empirical research conducted in laboratory sites revealed several strategies used by secondary school geometry teachers as they practice a pedagogy of guided inquiry using the *Geometric Supposers*. The teachers' strategies are discussed in terms of sociolinguistic theories about the teacher's role in defining the meaning of mathematical knowledge in the classroom. [See Lampert, (in press) for a fuller discussion of this research.]

One strategy for surfacing and using students' thinking was to have them work in pairs in the lab to produce a single report of their observations. Working in pairs the students had to challenge and justify assertions because they had to agree on what they would write down about the results of their inquiry. Usually they had to review these written notes and perhaps refine them as a homework assignment before turning them in to the teacher. Often teachers asked students to read from their papers during class discussion or posted students' writings for other members of the class to examine. Both of these methods served to bring the students' ideas into the public discourse of the classroom intellectual community.

The three chalkboard method made a visible connection between the results of the relatively private inquiry that occurred when students worked in pairs at the computer and the public discourse of the class lecture-discussion. On the first board the teacher wrote the students' findings in their own words. After examining these, the teacher asked students to offer more formal assertions about patterns in the data and wrote these conjectures on the second board. These might be translated by the teacher to incorporate standard terminology and forms and to transform some of the informal assertions into provable conjectures. On the third board the teacher took a more directive role in choosing one or more of the formalized student conjectures and writing it as it might appear in a geometry textbook. In this form the conjectures might lead to deductive arguments that turned into theorems.

Timing often made it difficult for teachers to weave students' homework assignments into class. One way they dealt with this problem was to cite conjectures developed by students in one class during discussion in a different class. This legitimated student thinking and seemed in some cases to set off productive competition among students who hoped their ideas would be taken to another class.

The *Supposer* gave students the means to check their conjectures empirically by generating a new figure to see whether a pattern they had observed held true. This is the formal procedure to follow in reasoning inductively, but students were often so sure of their ideas that they resisted checking. Then a student or teacher was likely to challenge, "Prove it!", thereby drawing the student into a deductive process. Teachers encouraged this kind of challenging and justifying during inquiry sessions in the lab and during class discussions. Students who were able to practice participating in such arguments in relative privacy with their lab partners built skills and confidence to help them face the riskier task of arguing in a whole-class discussion. Developing convincing, informal arguments also paved the way toward the more formidable challenge of producing the formal proofs demanded by their textbooks.

Recogonizing that fear of failure contributed to students' reluctance to think for themselves, teachers devised grading schemes to teach students about the difference between inquiry and authority as sources of knowledge. Conjectures could not be graded with the same "correct vs. incorrect" standard that is usually applied to students' school work. Teachers employed more qualitative ways of responding, using progressively more rigorous standards as students developed more sophisticated inquiry skills. They struggled to devise ways of testing inquiry skills and of weighing students' performance on these measures along with more conventional tests in assigning an overall course grade.

Teachers' strategies can be seen as shifting the sociolinguistic setting of the classroom. Using terms like *observation, conjecture, verify,* and *prove* in careful ways helped students learn to distinguish elements of mathematical reasoning such as data, ideas, and formal arguments. Establishing a language created the means for carrying out a kind of discourse which exemplified and legitimated the intellectual work of all members of a community. The strategies described above also changed the interaction patterns between teachers and students, thereby altering the participants' roles and responsibilities in relation to learning and knowing. Students were treated, and gradually came to perceive themselves, as sources of ideas and active participants in the process of generating and acquiring knowledge. Teachers made room for the kinds of tentative, exploratory statements that are the language of inquiry but that students often fear to use in classes where "right answers" are the coin of the realm. In this way they drew students into a process of collaborative knowledge building rather than the more usual one of reciting facts and established knowledge.

School Structures Affecting the Implementation of Guided Inquiry

Veteran geometry teachers endeavored to support the dissemination of the *Supposer*-based innovation to their colleagues. An enthnographic study of the three laboratory sites investigated the impact of school organizational values and structures on the spread of guided inquiry. The study yielded three case studies and an analysis of the interaction between school structures (e.g., physical characteristics, communication patterns, ways of making key decisions, and ways of organizing professional development programs) and aspects of the dissemination process (e.g., securing necessary support and the design of teacher instruction). [See Shepard & Wiske (in press) for a report on this research.]

The spread of an innovation requires support at two levels (Cox, 1983): assistance focused on the *context* to secure necessary approvals, facilities, schedules, and resources including time as well as tangible materials, and assistance for teachers focused on the *content* of the new practice. The person in the school who can arrange one form of assistance may not be in the best position to arrange other kinds of support. Administrators, for instance, often have control over the budgets and schedules that must be altered to create the appropriate *context*. They do not usually have, however, the intimate knowledge of an innovation's implications for day-to-day curriculum, instruction, and classroom management that is necessary for providing *content* assistance. Providing both kinds of support usually requires a division of labor among people who have different kinds of knowledge and power. Effective support for innovation requires enlisting the active participation of these people and coordinating their efforts into a coherent program.

This study revealed that an appropriate and coordinated division of labor is difficult to achieve. If administrators retain control over key resources such as time, schedules, and budgets, yet know little of the innovation's practical implications, they are unlikely to allocate these resources in ways that optimally support the innovation. If the teachers who understand the evolving forms of assistance they need to carry out the innovation are unable to shape or alter administrative decisions, the stage is set for people to work at cross purposes. The spread of the innovation proceeded most effectively when an instructional leader familiar with the innovation in the classroom had significant influence on decisions about curriculum and assessment, schedules, and time for and design of staff development activities.

A basic dilemma in supporting innovation involves balancing mandates with choice. While some studies (Huberman & Miles, 1984) have indicated that strong administrative leadership defines one effective school change scenario, this study revealed how central mandates can run afoul of innovations that depend upon teachers' exercising considerable autonomy. In one site, strong central administrators who perceived this innovation as primarily technological provided context assistance but made no provisions for helping teachers come to grips with the curricular and pedagogical demands of the innovation. In another case, a centrally mandated staff development program, originally created in response to teachers' requests for opportunities to learn about new developments, was so rigid in its structure that it seriously crippled efforts to spread the geometry innovation. The study indicated that, particulary for an innovation based on a guided inquiry approach, an effective staff development program lets teachers choose to participate and then provides adaptive assistance as they carry out the innovation in their own classrooms.

Training designs were influenced by school structures that shaped the recruitment of participants and constrained how and when participants could meet. For instance, in one case no formal instructional arrangements were made and the veteran and new teachers had to fit informal meetings into scarce niches in their crowded schedules. In a second case, a mandated staff development program established formal workshops at predetermined points throughout the year. In the third case, the veteran teachers managed to secure time for an introductory workshop and then negotiated for additional time as small groups of teachers clarified what kinds of assistance they needed in order to carry out the innovation in their classrooms. An effective dynamic in all sites involved a veteran teacher working in an apprenticeship model with a new teacher. While the the one-to-one, flexible structure of apprenticeship allowed implementation assistance to be tailored to teachers' evolving needs, the study also suggested that a very informal staff development structure is vulnerable. A more formal process of spreading an innovation is more likely to command attention as central decisions are made about allocating resources.

Balancing guidance with individual exploration is a fundamental pedagogical dilemma not just in planning classroom activities but also in designing in-service teacher education programs. The veteran teachers in the study juggled this balance in their own ways reflecting not only their personal instructional styles, but also their school contexts. Two teachers who were both committed to encouraging their students to invent in the classroom chose quite different instructional designs in working with their colleagues. The one working within a mandated staff development program found himself resorting to a relatively didactic instructional approach. This seemed to be the best way to deal with a widely varying group of participants and a formal workshop structure. The second teacher, operating within a context that encouraged teachers to set their own directions as continuing learners, fostered the spread of the innovation by allowing teachers to explore the software and sample lessons independently. As teachers devised their own ways of integrating the innovation into their practice, they were offered time, access to colleagues, and more focused assistance from veteran teachers. The second approach, made possible by a more flexible staff development program appeared better suited to this innovation. Through open-ended exploration with the new innovation, teachers opened themselves to the kind of rethinking about curriculum and pedagogical approach which seems to be a concomitant of fundamental educational change.

Overall, the study of the spread of an innovation in relation to school organizational contexts indicated ways that these three elements — the innovation itself, the implementation process, and the school setting — can either mesh well or work against each other. This innovation reflected a constructivist educational philosophy based on the assumption that learners must play an active part in making sense of new ideas and behaviors in relation to their prior knowledge and skills. School structures and norms that support a culture of inquiry (Goodlad, 1987), that encourage teachers to be active learners, that recognize teachers' authority in determining curriculum, and that provide support and flexibility for teachers to adapt new approaches support the spread of this kind of innovation. Such structures include providing **time** for teachers to explore new instructional innovations and **support** as they invent ways to connect them to their own practice; creating and building upon opportunities such as curriculum team meetings for teachers to exchange ideas about what and how to teach; establishing **communication** channels between administrators — at both the building and the central levels — and innovative teachers who understand how resources might be best allocated to support the spread of effective innovations. Similarly, a staff development program which values and reflects constructivist pedagogy is more effective in supporting this kind of innovation than a program that ignores or undermines such values. A "constructivist" staff development program would build on the interests teachers opt to pursue, would cultivate channels of professional support and stimulation, and would treat teachers in the ways teachers are expected to treat students, that is, as people who have the capacity and responsibility to make, share, and critique knowledge.

Implications and Recommendations

Over the course of two years, building on relationships developed earlier between researchers and classroom teachers, the Laboratory Site Project has cultivated a dialogue between educational theories and practice. This dialogue has depended on the gradual development among both school-based and university-based participants of trust, shared language, and convenient ways of getting together for in-class observations, at-school consultations, and reflective discussions. Such relationships take time and care to develop and sustain. One implication is that such relationships between researchers and school-based educators are a precious and costly resource, worth cultivating and preserving.

Further collaborative research is needed to better understand the nature, impact, and requirements of teaching for understanding through guided inquiry. Research on the impact of such teaching on student learning will require a clear sense of the desired outcomes — such as students' understanding of mathematical reasoning, ability to carry out such reasoning, and belief in their own capacity to participate productively in such work — and valid, reliable ways of measuring them. It will also require a clear picture of the independent variables and ways of measuring them. These would include not only the teaching strategies themselves, but also the underlying epistomology they reflect. The mechanistic reenactment of particular strategies by teachers without an accompanying shift in beliefs would be unlikely to work long lasting effects on either teachers or students.

Research must also examine the conditions in schools that constrain and support inquiry teaching. Assessment practices, ways of grouping and tracking students, rigid schedules made up of short periods, lack of time for teachers to think, talk, prepare, and respond to student work — all these appear to be powerful constraints. Understanding how traditional school structures impede this kind of teaching and how schools might be restructured to support it will point toward the kinds of reform that must complement efforts to design new curricula and educate teachers.

The results of this work also have implications for administrators, staff developers, teachers, and others who wish to promote the use of new technologies and of guided inquiry in instruction. The study affirms that incorporating this kind of innovation presents profound technological, curricular, and pedagogical challenges. Teachers need both guidance and support for their own process of invention and discovery in order to develop the new knowledge, skills, and beliefs necessary to incorporate such innovations into their practice. The process of providing such teacher education and support is one of coordinating "content" assistance as provided by advisors and colleagues with the provision of "context" resources, which usually depends of the active support of administrators. Moving from the transmission of knowledge to the construction of knowledge in the classroom implies not only deep change in teachers but deep change in the structure of schools.

DISSEMINATION

Synthesis and dissemination of the Center's work were ETC's primary activities during Year Five. The Center made special efforts to synthesize the findings of the research from individual projects and to make the results accessible to as many audiences as possible. Early in the year we convened an advisory group with particular expertise in outreach and dissemination. The members of this group — David Crandall of the Network, John H. Green and Eileen McSwiney of the Education Collaborative for Greater Boston, and Myles Gordon of the Education Development Center — met regularly with ETC central administrators to review the Center's products, activities, and audiences. Based on this analysis they proposed strategies for expanding dissemination efforts and reaching new audiences. These proposals were further discussed and evaluated by the ETC Agenda Group and the National Advisory Board. Many of the strategies and activities described below — including development and distribution of the Center's position paper and product catalogue, the series of seminars at the Institute for Educational Leadership, the distribution of prototype software, and the development of print materials to accompany the Center's videotapes — emerged from the deliberations of these groups.

Within the Center, Katherine Viator, ETC's Coordinator for Administration, oversaw many of the responsibilities associated with these efforts. In addition, David Niguidula was named to the position of Dissemination Coordinator.

Position Paper

In January, 1988, ETC released *Making Sense of the Future: A Position Paper on the Role of Technology in Science, Mathematics, and Computing Education*, a 22 page booklet synthesizing the findings of the Center's first four years of research. The document provided an overview of the Center's work in a style designed to make it accesible to a variety of audiences in educational research, policy, and practice.

The main section of the position paper presents three of the central themes which have emerged from and continue to shape ETC's work. The first section, **teaching for understanding**, describes the Center's overall pedagogical approach which emphasizes taking account of students' prior conceptions about a subject, integrating traditional instruction with episodes of inquiry learning, and teaching how knowledge is made within a discipline. The second section, **using new technologies to make a distinct educational contribution**, outlines the Center's findings on when computers can offer clear advantages over traditional teaching materials and make it possible to introduce ideas into the curriculum earlier and more effectively. ETC research projects have found that technology facilitates these goals by allowing learners to manipulate linked multiple representations of concepts and phenomena, by extending the range of manipulable objects to include intangible ones only available through technology, and by allowing educators to observe students' thinking about mathematical and scientific phenomena. The third section, **making research applicable to practice**, addresses the issues of how to take promising research-based innovations and make them into practical alternatives to current classroom practices. The Center's experience suggests that this effort requires bridging the cultures of schools and universities, infusing educational innovations into existing practice rather than replacing current practices, and studying the implementation process to understand its requirements.

The preparation of the position paper, a collaborative effort among the Center's senior researchers and administrators, established a framework for presenting ETC's efforts to many audiences. Themes from *Making Sense of the Future* became the centerpiece of the Center's dissemination efforts in Year Five. In the first three months of 1988, more than 25,000 copies of the booklet were distributed nationally and internationally. Among the audiences who received it were educational researchers, education officials, policy-making institutions, funding organizations, elected and appointed government officials at the state and federal level, educational and technical journals, computing industry personnel, publishers, corporate organizations, and education writers and journalists. A press release circulated by the Harvard University Press Office brought the document to the attention of approximately 600 education writers throughout the country. Resulting articles in the general press reached the public as well.

Dissemination of the position paper sparked interest in the Center's work in many places across the country, as ETC received requests for more information or for conference or workshop presentations. Seven state departments of education (Arizona, California, Florida, Maine, New York, Pennsylvania, and Virginia) and the school systems of New York City and Westchester County, N.Y., requested additional copies to distribute to their organizations. In addition, a steady stream of visitors has come to the Center seeking additional information and materials. Among those who have visited ETC are individuals or delegations from England, Peru, Israel, India, Wales, France, Egypt, Yugoslavia, Japan, Sweden, the New York State Department of Education, and the Westchester County Board of Cooperative Educational Services. The contacts made through the paper have resulted in the establishment of new working relationships and the opening of wider dissemination channels.

Product Catalogue

Shortly after the publication of the position paper, ETC also published a catalogue of products. Organized by subject area, and then by individual research groups, the catalogue lists and briefly describes the Center's currently available technical reports, conference reports, topical papers, videotapes, and prototype software and teaching materials (described in more detail below).

This catalogue was distributed at the Association for Supervision and Curriculum Development conference in Boston during March, 1988, at the American Educational Research Association conference in New Orleans during April, 1988, and at the National Educational Computing Conference in Dallas in June. It was also mailed to groups including the American Association of Educational Service Agencies and to nearly 2,000 superintendents of curriculum and instruction in science, mathematics, and computing. In addition, an on-line version of the catalogue appears on New York State Department of Education's electronic bulletin board, which is available to all educators in that state. The catalogue is also available on-line through the Network, Inc., in Andover, Massachusetts, OERI's Regional Laboratory for the Northeast and the Islands.

Institute for Educational Leadership Seminars

ETC's Fifth Year Plan declared the Center's intention to organize a conference in Washington, D.C., for representatives of the major education organizations and for policy makers from state and federal agencies. On January 26 and 27, 1988, the Center had the opportunity to address precisely these audiences through a series of seminars organized by the Institute for Educational Leadership (IEL). Judah L. Schwartz presented the Center's ideas at two small sessions (approximately 20 participants each) whose attendees included leaders from the National Congress of Parents and Teachers, the American Federation of Teachers, the National Foundation for Institute of Teaching (a branch of the National Education Association), the National Science Foundation, the National Governors' Association, the U.S. Department of Education, the Office of Educational Research and Improvement, the Council of Chief State School Officers, the Council for American Private Education, the AFL-CIO, and the Council for Basic Education. These small seminars offered the opportunity for the Center to share its views and findings with influential individuals in the educational community and to hear their reactions.

On the afternoon of January 27, Schwartz also addressed a larger audience at the Library of Congress. This event included 46 representatives from organizations such as the National Association of Elementary School Principals, the National Education Association, the National Governors' Association, the National Association of Public Television Stations, the Educational Testing Service, the Carnegie Corporation, the Council of Chief State School Officers, the National Academy of Sciences, the Association for Supervision and Curriculum Development, and eight Congressional Offices. The position paper was made available to these individuals and to the organizations they represent.

ETC National Conference

The Fifth Year Plan also mentioned a second conference to focus on the practical applications of the Center's work. This conference, entitled "Making Sense of the Future: Teaching for Understanding Using Computers in Schools," was organized in collaboration with several other research institutions and held on September 23 and 24, 1988, at the Harvard Graduate School of Education. Attended by over 200 educators, the conference synthesized recent work by ETC and the participating organizations on the role of new technologies in improving science and mathematics instruction in the schools. Panel presentations to the whole group presented alternative views on the themes of the position paper — teaching for understanding, the contribution of technology, and implementation issues. More than two dozen small group sessions focused on particular examples of innovative software and approaches for supporting the use of new technologies to improve science and mathematics education.

A keynote address by Albert Shanker, President of the American Federation of Teachers, set a broad context for the conference by discussing how the current structure of schools might be altered to promote the kinds of educational approaches presented at the conference. The first panel, moderated by David Perkins of ETC and featuring presentations by Marlene Scardamalia of the Ontario Institute for Studies in Education and Roy Pea of the Institute for Research on Learning, then examined the concept of understanding and what it means to teach for understanding. Scardamalia described her work on a computer environment designed to support students' self-directed inquiry learning. Pea discussed the contribution to education of the intelligence embodied in the tools we use, pointing out how technology can assume many computational and representational burdens, freeing learners to focus on conceptual issues.

The second panel, moderated by Judah Schwartz, addressed the contribution of technology to teaching for understanding in mathematics and science. In the first presentation Samuel Gibbon of Bank Street College discussed the role of stories in his work with interactive television, particularly in the *Second Voyage of the Mimi*. He argued that stories can be educationally powerful because we remember the information embedded in them better than when we encounter the same information in more didactic ways. Andee Rubin of Bolt Beranek and Newman presented examples — such as BB&N's ELASTIC, a program to teach statistical reasoning, and Kids Network, a national database on acid rain — of how technology can enable students to collect data and conduct inquiry in the ways that mathematicians and scientists do.

Finally, the third panel, moderated by Martha Stone Wiske, examined implementation issues associated with technological innovations and inquiry approaches to teaching and learning in schools. Magdalene Lampert of Michigan State University focused on the teacher's role in the mathematics classroom and on what teachers must know and do to teach for understanding using computers. Karen Sheingold of Bank Street College discussed ways that schools might be reorganized to support inquiry and the kinds of assistance that teachers and students need to accomplish this goal.

The conference's nearly thirty small sessions included several presented by ETC projects and consortium member organizations (including Educational Testing Service, Education Development Center, Education Collaborative for Greater Boston, and WGBH Educational Foundation). Others were given by representatives of Bank Street College, Bolt Beranek and Newman Inc., Lesley College, and Technical Education Research Centers. Additional small group sessions included "Models of Management and Leadership for Integrating New Technologies in Schools" by four teachers named by the National Education Association as Christa McAuliffe Educators, "Educational Innovation as Seen Through the Eyes of a Software Publisher" by Marge Kosel of Sunburst Communications, and "Private Sector Support for Improved Public Education" by Kenneth R. Rossano of the Bank of Boston. Many of these sessions were presented jointly by researchers and public school teachers.

Other Presentations

The Center's dissemination efforts also included presentations by ETC researchers in a variety of forums through the year. In September, NBC News interviewed Judah Schwartz for a series on "Computers and Education," aired on the NBC Nightly News.

In March, 1988, ETC presented one of the Distinguished Lectures at the conference for the Association for Supervision and Curriculum and Development. This presentation, entitled "Technology as a Process of Teaching and Learning," was given by David Perkins, Judah Schwartz, and Martha Stone Wiske, with Carolee Matsumoto of the Education Development Center participating as respondent.

As in past years, a number of ETC associates presented the Center's work at the American Educational Research Association conference in April. Judah Schwartz, Ellen Mandinach, Carol Smith, Marianne Wiser, Martha Stone Wiske, Richard Houde, Mary Maxwell West, Susan Carey, David Perkins, James Kaput, Daniel Chazan, Magdalene Lampert, and Philip Zodhiates presented during this conference.

Also in April, ETC associates from the mathematics research groups presented at the National Council of Teachers of Mathematics conference in Chicago. James Kaput and Judah Schwartz discussed topics of interest to mathematics teachers, curriculum supervisors, and researchers.

In March, Martha Stone Wiske spoke on "Technology and the Teacher's Role" at the Education Connections conference sponsored by Apple Computer, Inc., in Boston, New York, and Atlanta, and in June, Steven Schwartz presented the work of the Programming Group at the National Educational Computing Conference in Dallas.

In May, Mary Maxwell West and Judah L. Schwartz spoke to the National Academy of Education on "Computer Communications and Education."

Videotape

The third of a series of three videotapes produced jointly by ETC and Education Development Center was completed in April. *A Whole Lot More...: Teachers Talk about*

Computers in the Classroom runs 29 minutes and f .tures a discussion involving eleven elementary and secondary teachers, moderated by Judah Schwartz. The discussion is interwoven with classroom footage that provides several images of teaching with computers and illustrates the influences these teachers observed on student motivation and performance, the social dynamics of their classrooms, and their teaching styles and teaching opportunities. Participants also reflect on the special demands that computers create for schools, particularly for the inservice education of teachers. The tape was developed primarily for educational policy audiences but is useful viewing for teachers, school administrators, and parents as well.

This tape completes a series that began with two earlier tapes, *New Tools for Learning: Using Computers in Science Education* and *Image, Graph, Symbol: Representation and Invention in the Learning of Mathematics*. Taken together, they cover the three elements — subject matter, teachers, and technology — that must be brought into harmony in ETC's educational approaches. Print materials that now accompany each tape provide an overview of the tape's contents, suggestions for use with particular audiences, and possible discussion questions.

During Year Five ETC sold a total of 224 videotapes to interested parties.

Technical Reports

ETC published twenty-three technical reports during Year Five, which added to the existing list of reports available by mail or in person from the Center. Also released this year were special project reports on "A Model Program in Science, Mathematics, and Technology" (funded jointly by OERI and the Massachusetts Board of Regents of Higher Education) and "How Technology Affects Teaching" (funded jointly by OERI and the U.S. Office of Technology Assessment). 2,184 technical reports were sold by the Center during Year Five).

Prototype Materials

This year ETC also began distribution of software and teaching materials produced by research groups. These products were made available as prototype materials which have shown promise when used in classrooms under research conditions and in the context of a larger inquiry into teaching and learning. Although not yet in final, stand-alone form, the materials are sufficiently well developed and tested to be useful to other researchers in science, mathematics, and computing education or to teachers willing to adapt an experimental unit for use in their classes. ETC hopes that adding these products to the others already disseminated by the Center will get them quickly into the hands of some who might benefit from using them (176 copies were sold in Year Five). In the meantime, ETC continues to pursue prospects for funding the full development and publication of these materials. The prototype products now available are:

The *Prototype Programming Metacourse*, a series of ten one-period scripted lessons each addressing one of the cognitive skills needed in programming. Designed to be integrated at the teacher's discretion into an introductory course in BASIC programming, the lessons cover such topics as the "data factory" (a visual model of the computer), methods for thinking about statements and programming patterns. Supplemental materials, including Animated Data Factory software, a minimanual of BASIC statements, and posters, are also available.

The *Prototype Word Problems Software* offers a series of software environments for solving problems that involve multiplication, division, and ratio reasoning. Described in detail in *A Concrete-to-Abstract Software Ramp: Environments for Learning Multiplication, Division, and Intensive Quantity* (Technical Report TR87-8), these environments lead the user from easily graspable concrete representations in which icons are manipulated on the screen to the more abstract representations of tables of numerical data, coordinate graphs, and algebraic equations. The package includes two disks with 11 programs, outlines of lessons used in research conducted with the software, and an overview of the group's research.

Using the *Prototype Weight/Density Software and Teaching Materials*, students can simulate sinking and floating of objects with different weights, masses, and densities. They can also create and compare objects which differ in weight, size, and density, and examine how increased and decreased temperatures affect these quantities. Designed with middle school students in mind, the programs emphasize and make accessible the concepts of modeling and experimentation in scientific inquiry. Accompanying the software are examples of lessons on the concepts of weight, mass, density, and modeling. Not all of the lessons use the software; some encourage discussion in the classroom, while others describe experiments to be done in a science lab without computers. The software includes a series of six programs on two disks to be run on an Apple // series computer.

The *Prototype Heat/Temperature Software* illustrates several components involved in understanding the concepts of heat and temperature, such as the relation among heat, temperature, and mass, and conduction and specific heat. The programs include models of molecular movement and energy transfer within a system. Distributed with lesson plans, worksheets, and homework assignments for the students, the software comes on a set of five disks, four running on IBM machines and one running on Apple // computers.

The *Prototype Nature of Science Teaching Materials* comprise plans for four weeks of lessons aimed at teaching students about the purpose and methods of scientific inquiry. The lessons include an introductory segment, a two-week segment on yeast that investigates the phenomenon of bread dough rising, a one-to-two-week segment on linguistics in which students build theories about English language phenomena, and a wrap-up lesson.

Published Software

In addition to these prototype software products, ETC has continued to disseminate two other pieces of software developed at the Center. *Immigrant* is an experimental curriculum unit designed to recreate the experience of Irish immigrants in Boston, 1840-1860. Developed to illustrate the use of applications software in the social studies, the integrated software package contains AppleWorks™ datafiles with lists of passengers, jobs, and housing; spreadsheet templates which allow students to calculate food, clothing, and household expenses; and a wordprocessor. *Common Ground* is an easy-to-use, microcomputer-based electronic conferencing software used at ETC for supporting collegial exchange among teachers. The system, which is also suitable for other conferencing needs, provides for enrolled participation, private messages, and public discussions for a maximum of 100 members at a time. This year ETC sold 152 copies of these pieces of software.

Books

The results of ETC's first five years of work will be summarized in three books currently in varying stages of completion. The first, a volume on the long-term future of technology in education, became available from Erlbaum Associates in September 1988. Entitled *Technology in Education: Looking Toward 2020,* the book presents chapters by the members of ETC's 2020 Panel, convened in 1985 to envision a desirable state of affairs for technology and education 35 years hence and to suggest how to arrive at that goal. Contributors to the book include: Thomas K. Landauer on "Education in a World of Omnipotent and Omniscient Technology," Andrea A. DiSessa on "What Will it Mean to be 'Educated' in 2020?", Elliot Soloway on "It's 2020: Do You Know What Your Children Are Learning in Programming Class?", Roy Pea on "Putting Knowledge to Use," and David Cohen on "Educational Technology and School Organization." The volume is edited by Philip Zodhiates and Raymond S. Nickerson, who wrote the overview and concluding chapters.

The second book, tentatively titled *Teaching for Understanding in the Age of Technology,* will elaborate the same cross-project themes that were developed in the Center's position paper and national conference. During the summer and early fall, editors David Perkins, Judah Schwartz, Mary Maxwell West, and Martha Stone Wiske met frequently to clarify the book's focus and identify contributors to its three sections: Understanding Understanding; Using Technology to Make a Distinct Contribution; and Connecting Educational Research and Practice. ETC associates who will contribute to the book include Marianne Wiser on using the history of science to understand student misconceptions; Susan Carey on science understanding, human development, and metaconceptual awareness; David Perkins on a multifaceted model of understanding; Judah Schwartz on moving from the particular to the general and on the "right-sized byte-size"; James Kaput on multiple representations as a vehicle for understanding; E. Paul Goldenberg on multiple representations as a vehicle for understanding understanding; Carol Smith on models as vehicles of learning; Steven Schwartz on finding the metacurriculum, Martha Stone Wiske on collaborative research and on the implications of new technologies for school organization (with Tony Cline). Additional contributors will include Raymond S. Nickerson on what it means to understand; Carlos Vasco on the history of making mathematics understandable; Roy Pea on the development of distributed intelligence; David Cohen on the history of technological innovations in schools; Margaret Vickers on new technologies and teachers' roles; and Magdalene Lampert on teaching for understanding in the classroom. Draft chapters are to be submitted to the editors in November; the manuscript is expected to be ready for submission to a publisher by the end of January.

Finally, work is proceeding on a third book, *The* Geometric Supposer *Reader,* to be published by Erlbaum Associates. The *Supposer* (developed at Education Development

Center and distributed by Sunburst Communications) has been the basis for the ETC Geometry Project's work, and the results of that research will be included in the book. In addition, the volume will feature chapters on the design of the software and the experience of teachers who have used it in their classrooms. Contributors will include Judah Schwartz, Richard Houde, Daniel Chazan, Myles Gordon, Michal Yerushalmy, Marge Kosel, James Kaput, Magdalene Lampert, Martha Stone Wiske, and others. The book will be addressed to researchers, curriculum developers, innovative teachers and educators, and inservice directors.

Articles

Articles by ETC associates have appeared in journals addressing many different audiences. These have included:

Chazan, Daniel, and Richard Houde, in press. How to Use Conjecturing and Microcomputers to Teach Geometry. Reston, VA.: National Council of Teachers of Mathematics.

Chazan, Daniel, July 1988. "Proof and Measurement: An Unexpected Misconception." In Proceedings of the Twelfth International Conference of the Psychology of Mathematics Education, Budapest, Hungary.

Goldenberg, E. Paul, 1988. "Mathematics, Metaphors and Human Factors." Journal of Mathematical Behavior, 7:135-173.

Goldenberg, E. Paul, in press. "Exploring Decimals: A Conversation with Fourth Graders." Arithmetic Teacher.

Goldenberg, E. Paul and M. Kliman, in press. "Methaphors for Understanding Graphs: What You See is What You See." Journal of Mathematical Behavior.

Kaput, James J., in press. "Supporting Concrete Visual Thinking in Multiplicative Reasoning: Difficulties and Opportunities." In Focus on Learning Problems in Mathematics.

Kaput, James J., in press. "Concrete Beginnings for Multiplication, Division and Ratio." Journal of Mathematical Behavior, special issue on multiplication and division, edited by B. Greer.

Kaput, James J., in press. "The Cognitive Foundations of Modeling with Intensive Quantities." In Proceedings of the Second Annual Conference on the Teaching of Mathematical Modeling, Kassel, FRG.

Lampert, Magdalene, in press. "Connecting Mathematical Teaching and Learning," Paper prepared for the First Wisconsin Symposium on Research on Teaching, Learning and Mathematics, Madison, Wisconsin, May 16, 1988.

Mandinach, Ellen B., 1988. "Executive Summary of the STACI Project." Paper prepared for Apple Computer, Inc. Princeton, NJ: Educational Testing Service.

Nickerson, Raymond and Philip Zodhiates, eds., 1988. Technology and Education: Looking Toward 2020. Hillsdale, NJ: Erlbaum.

Perkins, David N., Steven Schwartz and Rebecca Simmons, 1988. "Instructional Strategies for the Problems of Novice Programmers." Pp. 153-178 in Teaching and Learning Computer Programming, edited by R. Mayer. Hillsdale, NJ: Erlbaum.

Perkins, David N. and Rebecca Simmons, in press. "Patterns of Misunderstanding: An Integrated Model of Misconceptions in Science, Math and Programming." Review of Educational Research.

Schwartz, Steven, David Niguidula, and David N. Perkins, March 1988. "A Vitamin Shot for BASIC Classes." Computing Teacher.

Wiser, Marianne, 1988. "The Differentiation of Heat and Temperature: History of Science and Novice-Expert Shift." Pp. 28-40 in Ontogeny, Phylogeny, and Historical Development, edited by S. Strauss. Norwood, NJ: Ablex.

Courses

Both Co-Directors of ETC are members of the faculty of the Harvard Graduate School of Education, where they offer courses on topics related to the Center's work. This year, Martha Stone Wiske's "Seminar on The Computer as an Educational Innovation" examined the complexities of integrating computers into schools. Judah L. Schwartz offered an "Educational Software Design Laboratory," which he cotaught with George Brackett of George Brackett Associates, a software design company. Both courses enriched and extended the ideas and approaches used in ETC research projects. The Center's work is similarly extended through the courses taught by ETC researchers who are members of the faculties of other universities.

REFERENCES

Behr, M., Lesh, R., Post, T., & Silver, E. (1983). Rational number concepts. In R. Lesh & M. Landau (Eds.), *Acquisition of mathematics concepts and processes*. New York: Academic Press.

Bell, A., Fischbein, E. & Greer, B. (1984). Choice of operation in verbal problems: The effects of number size, problem structure and context. *Educational Studies in Mathematics*, 15, 129-147.

Black, S.D., Levin, J., Mehan, H., & Quinn, C.N. (1983). Real and non-real time interaction: Unraveling multiple threads of discourse. *Discourse Processes*, 5, 59-75.

Campbell, P. and J. Fey. (1988). New goals for school mathematics. In R. Brandt (Ed.),*The Content of the Curriculum*. Alexandria, VA: Assoc. for Supervision and Curriculum Development, 1988 Yearbook, pp. 53–73.

Carey, S., Evans, R., Honda, M., Jay, E. and Unger, C. (1988). An experiment is when you try it and see if it works: A study of junior high school students' understanding of the construction of scientific knowlege. Technical Report TR88-19. Cambridge, MA: Educational Technology Center.

Carpenter, T.P., Lindquist, M., Mathews, W., & Silver, E. A. (1983). Results of the third NEAPA mathematics assessment: Secondary school. *Mathematics Teacher* 76, 652–659.

Carpenter, T., Moser, J. & Romberg, T. (1982). *Addition and subtraction: A cognitive perspective*. Hillsdale, NJ: Erlbaum.

Chazan, D. (1988). *Similarity: Exploring the understanding of a geometric concept*. Technical Report TR88–15. Educational Technology Center. Harvard Graduate School of Education.

Chazan, D. (in press). Proof and Measurement: An Unexpected Misconception. In *Proceedings of the Twelfth International Conference of the Psychology of Mathematics Education*. Budapest, Hungary, July 1988.

Chazan, D. (1988). *Posing problems: One aspect of bringing inquiry into classrooms*. Technical Report TR88–21. Educational Technology Center. Harvard Graduate School of Education.

Cole, H. (1968). " An Analysis of the effects of a structured teaching approach developed from the work of Piaget, Bruner and others." Unpublished Doctoral Dissertation: State University of New York at Buffalo.

College Entrance Examination Board. (1985). *Academic Preparation in Mathematics: Teaching for transition from high school to college*. J. Kilpatrick (Ed.). New York: Author.

Corbitt, M. K. (1981). *Results from the Second Mathematics Assessment of the National Assessment of Educational Progress*, Reston, VA: National Council of Teachers of Mathematics.

Cox, P. L. (1983). Complementary roles in successful change. *Educational Leadership,41* (3), 10-13.

Craine, T. V. (1985). "Integrating Geometry into the Secondary Mathematics Curriculum." In C. R. Hirsch and M. J. Zweng (Eds.),*The Secondary School Mathematics Curriculum*. Reston, VA: National Council of Teachers of Mathematics, 119–135.

Crandall, D., et al. (1982). *People, policies, and practices: Examining the chain of school improvement, Vols. I-X*. Andover, MA: The NETWORK, Inc.

Eccles, F. M. (1972). The forum: What should become of the high school geometry course? *Mathematics Teacher* 65, 151–154.

Feenberg, A. (1985). Moderating an educational teleconference. Unpublished Manuscript, Western Behavioral Sciences Institute, La Jolla, CA.

Fehr, H. F. (1972). The forum: What should become of the high school geometry course? *Mathematics Teacher* 65, 102-103.

Feuerstein, R. (1979). *The dynamic assessment of retarded performers: The learning potential assessment device, theory, instruments, and techniques*. Baltimore: University Park Press.

Feuerstein, R. (1980). *Instrumental enrichment: An intervention program for cognitive modifiability*. Baltimore: University Park Press.

Fey, J. T. (Ed.) (1984). *Computing and mathematics: The impact on secondary school curriculums*. Reston, VA: National Council of Teachers of Mathematics.

Fischbein, E., Deri, M., Nello, M., & Marino, M. (1985). The role of implicit models in solving verbal problems in multiplication and division. *Journal for Research in Mathematics Education* 16, 3-17.

Forrester, J. W. (1968). *Principles of systems*. Cambridge: Massachusetts Institute of Technology Press.

Goffman, E. (1974). *Frame analysis: An essay on the organization of experience*. New York: Harper & Row.

Goldenberg, E. P. (1988a, in press). Mathematics, metaphors, and human factors. *Journal of Mathematical Behavior*, 7(2).

Goldenberg, E. P. (1988b, in press). Exploring decimals: a conversation with fourth graders. *The Arithmetic Teacher*.

Goldenberg, E. P., Harvey, W., Lewis, P. G., Umiker, R. J., West, J., & Zodhiates, P. (1988). *Mathematical, technical, and pedagogical challenges in the graphical* *representation of functions*. Technical Report TR88-4. Cambridge, MA: Educational Technology Center.

Goldenberg, E. Paul, and M. Kliman, (in press). Metaphors for understanding graphs: What you see is what you see. *Journal of Mathematical Behavior*.

Goodlad, J. (ed.) (1987). *The ecology of school renewal. Eighty-sixth yearbook of the National Society for the Study of Education*. Chicago: University of Chicago Press.

Hall, G.E., & Loucks, S.F. (1978). Teacher concerns as a basis for facilitating and personalizing staff development. *Teachers College Record*, 80 (1), 36-53.

Hall, G.E., & Hord, S.M. (1987). *Changes in schools: Facilitating the process*. Albany: State University of New York Press.

Hewson, M.G. (1982). *Students' existing knowledge as a factor influencing the acquisition of scientific knowledge*. Unpublished Doctoral Disseration: University of the Witwatersrand, Johannesburg, South Africa.

Hoffer, A. (1981). Geometry is more than proof. *Mathematics Teacher* 74, 11–18.

Huberman, M. & Miles, M. (1984). *Innovation up close*. New York: Praeger.

Hunting, R. & Sharpley, C. (1988). Fraction knowledge in preschool children. *Journal for Research in Mathematics Education*, 19 (2) 175-180.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic Books.

Kaput, J. (1985). *Multiplicative word problems and intensive quantities: An integrated software response*. Technical Report TR85-19. Cambridge, MA: Educational Technology Center.

Kaput, J. (1987). Toward a theory of symbol use in mathematics. In C. Janvier (Ed.), *Problems of representation in mathematics learning and problem solving*. Hillsdale, NJ: Erlbaum.

Kaput, J. (in press a). Linking representations in the symbol system of algebra. In C. Kieran & S. Wagner (Eds.), *A research agenda for the teaching and learning of algebra*. Reston, VA: National Council of Teachers of Mathematics; and Hillsdale, NJ: Erlbaum.

Kaput, J. (in press b). Relationships between constructivism and representation. In E. von Glasersfeld (Ed.), *Constructivism in mathematics education*. Dordrecht, Holland: Reidel.

Kaput, J. (in press c). The role of concrete representations in multiplicative structures: Part 1. Multiplication and division. Part 2. Ratio Reasoning. *Journal of Mathematical Behavior*.

Kaput, J., Luke, C., Pattison-Gordon, L. & West, M. M. (1988). Concrete representations for ratio reasoning. In M. Behr, C. Lacampagne, M. M. Wheeler (Eds.), *Proceedings of the 10th Annual Meeting of the PME-NA*. DeKalb, Illinois.

Kaput, J., Luke, C., Poholsky, J., & Sayer, A. (1987). Multiple representations and reasoning with intensive quantities. In J. Bergeron, C. Kieran, & N. Herscovics (Eds.), *Proceedings of the 11th Annual Meeting of the PME-NA*, Vol.1, University of Montreal.

Kaput, J., & L. Pattison-Gordon (1987). *A concrete-to abstract software ramp: Environments for learning multiplication, division, and intensive quantity*. Technical Report TR87-8. Cambridge, MA: Educational Technology Center.

Katz, M.M., McSwiney, E., & Stroud, K. (1987). Facilitating collegial exchange among science teachers: An experiment in computer-based conferencing. Technical Report TR 86-14. Cambridge, MA: Educational Technology Center.

Kerr, E. B., and Hiltz, S.R. (1982). *Computer-mediated communication systems*. New York: Academic Press.

Kuhn, D., Amsel, E., & O'Loughling, M. (1988). *The development of scientific thinking skills*. Orlando, FL: Academic Press.

Lampert, M. (1988). *Teachers' thinking about students' thinking about geometry: The effects of new teaching tools*. Technical Report TR88-1. Cambridge, MA: Educational Technology Center.

Lampert, M. (1988). *Teaching that connects students' inquiry with curricular agendas in schools*. Technical Report TR88-27. Cambridge, MA: Educational Technology Center.

Levin, J.A., Kim, H., and Riel, M.M. (1988, April). Instructional interactions on electronic message networks. Paper presented at the annual meeting of the American Educational Research Organization, New Orleans.

Mandinach, E. B. (1986). *Systems thinking and curriculum innovation: A naturally occurring classroom study* (STACI Rep. No. 1). Princeton, N.J.: Educational Testing Service.

Mathematical Science Education Board. (1987, January). [Press release]. Washington, DC: National Research Council.

McKnight, C., Crosswhite, F. J., Dossey, J. A., Kifer, E., Swafford, J. O., Travers, K., & Cooney, T. J. (1987). *The underachieving curriculum: Assessing U.S. school mathematics from an international perspective*. Champaign, IL: Stipes.

National Science Board Commission on Precollege Education in Mathematics, Science, and Technology. (1983). *Educating Americans for the 21st century*. Washington, DC: National Science Foundation.

Osborne, R.J., & Wittrock, M.C. (1983). Learning science: A generative process. *Science Education*. 67 (4), 489-508.

Palinscar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction*, **1**, 117-175.

Piaget, J., & Inhelder, B. (1974). *The child's construction of quantities.* London: Routledge and Kegan Paul.

Quintero, A. (1980). The role of semantic understanding in solving multiplication word problems. Doctoral Thesis, Department of Mathematics, Massachusetts Institute of Technology.

Resnick, L. B. (1987). *Education and learning to think.* Washington, DC: National Academy Press.

Richmond, B. (1985). *STELLA* [Computer program]. Lyme, NH: High Performance Systems.

Rowell, J.A., & Dawson, C.J. (1977a). Teaching about floating and sinking: An attempt to link cognitive psychology with classroom practice. *Science Education*, **61**, 243-251.

Rowell, J.A., & Dawson, C.J. (1977b). Teaching about floating and sinking: Further studies toward closing the gap between cognitive psychology and classroom practice. *Science Education*, **61**, 527-540.

Rowell, J.A., & Dawson, C.J. (1983). Laboratory counterexamples and the growth of understanding in science. *European Journal of Science Education*, **5**, 203-215.

Schoenfeld, A. (1986). On having and using geometric knowledge. In J. Hiebert (Ed.), *Conceptual and Procedural Knowledge: The case of mathematics.* Hillsdale, NJ: Erlbaum.

Schwartz, J. L., Yerushalmy, M., and Education Development Center (1985–87). *The GEOMETRIC SUPPOSERS.* Pleasantville, NY: Sunburst Communications.

Schwartz, J. (1984). *An empirical determination of children's word problem difficulties: Two studies and a prospectus for further research.* Technical Report TR84-5. Cambridge, MA: Educational Technology Center.

Schwartz, J. (1988). Referent preserving and referent transforming quantities. In J. Hiebert & M. Behr (Eds.) *Number concepts and operations in the middle school.* Reston, VA: National Council of Teachers of Mathematics; and Hillsdale, NJ: Erlbaum.

Shepard, J.W. & Wiske, M.S. (1988). *Extending technological innovations in schools: Three case studies and analysis.* Technical Report TR88-29. Cambridge, MA: Educational Technology Center.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition*, **21**, 177-237.

Smith, C., Snir, J., and Grosslight, L. (1987). *Teaching for conceptual change using a computer-based modeling approach: The case of weight/density differentiation.* Technical Report TR87-11. Cambridge, MA Educational Technology Center.

Smith, D. (1984). Cognitive processes and students' misconception in science. Paper presented at the annual meeting of the Northeastern Educational Research Association.

Snir, J., Smith, C., & Grosslight, L. (1988). *The truth but not the whole truth: An essay on building a conceptually enhanced computer simulation for science teaching*. Technical Report TR88-18. Cambridge, MA: Educational Technology Center.

Strauss, S., Globerson, T., & Mintz, R. (1983). Theinfluence of training for the atomistic schema on the development of the density concept among gifted and nongifted children. *Journal of Applied Developmental Psychology*, 4, 125-147.

Usiskin, Z. (1980). What should not be in the Algebra and Geometry curricula of average college-bound students? *Mathematics Teacher* 73, 413-426.

Usiskin, Z., & Bell, M. (1983). *Applying arithmetic: A handbook of applications of arithmetic*. Part II. Operations. Chicago: Department of Education, University of Chicago.

Vergnaud, G. (1983). Multiplicative structures. In R. Lesh & M. Landau (Eds.), *Acquisition of mathematics concepts and processes*. New York: Academic Press.

Voss, J. F. (1978). Cognition and instruction: Toward a cognitive theory of learning. In A. M. Lesgold, J. W. Pellegrino, S. D. Fokkema, & R. Glaser (Eds.), *Cognitive psychology and instruction*. New York: Plenum Press.

Waugh, M., Miyake, N., Levin, J.A., & Cohen, M. (1988, April). Problem solving interactions on electronic networks. Paper presented at the annual meeting of the american Educational Research Association, New Orleans.

White, B.Y., & Horwitz, P. (1987). *Thinker Tools: Enabling children to understand physical laws*. Report #6470. Cambridge, MA: Bolt Beranek and Newman Laboratories, Inc.,

Wiser, M., Kipman, D., and Halkiadakis, L. (1988). *Can models foster conceptual change? The case of heat and temperature*. Technical Report TR88-7. Cambridge, MA: Educational Technology Center.

Wiske, M.S., Niguidula D., Shepard, J.W. (1988). *Collaborative research goes to school: Guided inquiry with computers in classrooms*. Technical Report TR88-3. Cambridge, MA: Educational Technology Center.

Wiske, M.S. & Houde, R. (1988). *From recitation to construction: Teachers change with new technologies*. Technical Report TR88-28. Cambridge, MA: Educational Technology Center.

Yerushalmy, M. (1986). Induction and Generalization: An experiment in teaching and learning high school geometry. Unpublished Doctoral Dissertation. Cambridge, MA: Harvard Graduate School of Education.

Yerushalmy, M., Chazan, D., & Gordon, M. (1987). *Guided inquiry and technology: A year-long study of children and teachers using the* GEOMETRIC SUPPOSERS, Technical Report TR88–6. Cambridge, MA: Educational Technology Center.

Zweng, M. (1964). Division problems and the concept of rate. *Arithmetic Teacher*, 11, 547-556.

Zweng, M. (1972). The fourth operation is not fundamental. *Arithmetic Teacher*. 19, 623-627.